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Vol. 2

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Vol. 2

Advanced Polymer Components Volume 2

Dr. John Rusek

OLAC PL/RKS
Phillips Laboratory
Edwards AFB CA 93524

October 1995

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

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PHILLIPS LABORATORY
Propulsion Directorate
AIR FORCE MATERIEL COMMAND
EDWARDS AIR FORCE BASE CA 93524-7001

FOREWORD

This in–house final report was prepared by OLAC PL/RKS, Edwards AFB CA, for Operating Location AC, Phillips Laboratory, Edwards AFB CA 93524–7001. Project Manager was Dr. John J. Rusek.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the SF Form 298.

Dr. JOHN J. RUSEK
Project Manager

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Deputy Director
Propulsion Sciences Division

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13. ABSTRACT (MAXIMUM 200 WORDS)

The Advanced Polymer Components Initiative began in December 1989. The initial purpose of the program was to explore advanced engineering polymers for use as rocket propulsion components. As research progressed it became apparent that advanced thermoplastics in general were highly dependent on processing and post-processing as well as on chemical composition and morphology. This realization led to a branching of the original objective into an applications research goal and a fundamental research goal. This report, coupled with PL-TR-92-3018, PL-TR-92-3018 Vol. 2 and PL-TR-92-3056, comprise a summary of the entire Advanced Polymer Components Initiative.

14. SUBJECT TERMS

thermotropic liquid crystal polymers; hybrid rocket; advanced polymer components; rocket propulsion; thermotropic resin

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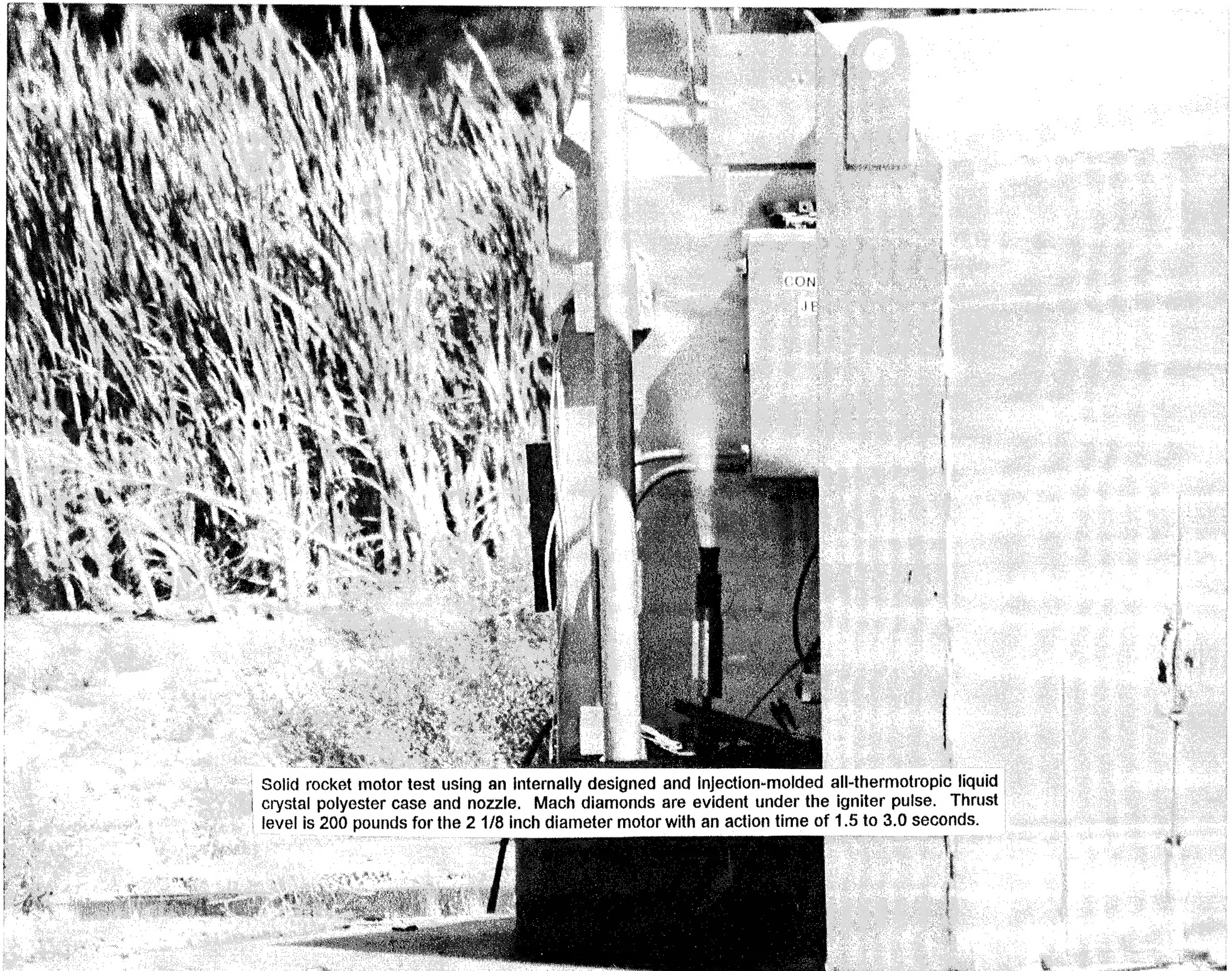

Solid rocket motor test using an internally designed and injection-molded all-thermotropic liquid crystal polyester case and nozzle. Mach diamonds are evident under the igniter pulse. Thrust level is 200 pounds for the 2 1/8 inch diameter motor with an action time of 1.5 to 3.0 seconds.

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RDL AFOSR Final Report

CRYOGENIC TESTING OF LIQUID CRYSTAL POLYMERS

Jason Phillips
OLAC/RCC
Phillips Laboratory

As a high school student, the future of my chosen field is directly in my hands. What I, and thousands like me, do has a profound effect on the future of American science. With that in mind I chose to participate in an eight week summer apprenticeship at Phillips Lab, located at Edwards Air Force Base. This has resulted in a variety of different benefits that if used to their full potential could help me immensely in the near future.

Computers

My knowledge of computers drastically increased during my stay here. Before entering this program I was fairly proficient with most Apple computers and I could meander through most of the other standard personal computers (PCs). Now I am fully competent with a Macintosh and have a working knowledge of other systems.

In the everyday world people see PCs as little more than high powered type-writers. At Phillips Laboratory I learned to see computers as an advanced all-purpose tool. A tool so powerful it can do things thousands of miles away. It's this mode of thinking that separates your average PC user from the professional.

College Application

Not all that I learned was expected. I found a surprising number of engineers had recently gone back to college for one reason or another and their advice will hopefully prove to be very helpful. The college co-ops also working here for the summer have proven to be invaluable. They possess knowledge of the college experience from the

eyes of someone closer to my own age. The information they imparted to me was found to be both interesting and helpful.

Engineering

Engineering, especially the actual development of working pieces, is a team effort. Learning this was probably the most important part of my apprenticeship. Engineers are not the only vital link in the scientific work force. Mechanics, secretaries, draftsmen and other support personnel are just as vital to scientific research.

Scientific Research

The main goal of my summer was to engage in actual, worthwhile scientific research. I worked on a project that involved work on Liquid Crystal Polymers (LCPs). LCPs look promising for future aerospace applications. They are light weight, have a high strength to weight ratio at room temperature, and should possess an even greater strength in cold environments.

LCPs are very structured on a molecular level, much like crystals (hence the name liquid crystal polymer). Due to the nature of the molecular bonding, the outer layer of cells (referred to as the skin of the LCP from here) is much stronger than the rest of the material. This layer of skin is responsible for the high strength to weight ratio mentioned above.

These LCPs are to be tested for application in a cryogenic turbopump. A cryogenic material is simply an extremely cold liquid gas,

Diagram #1

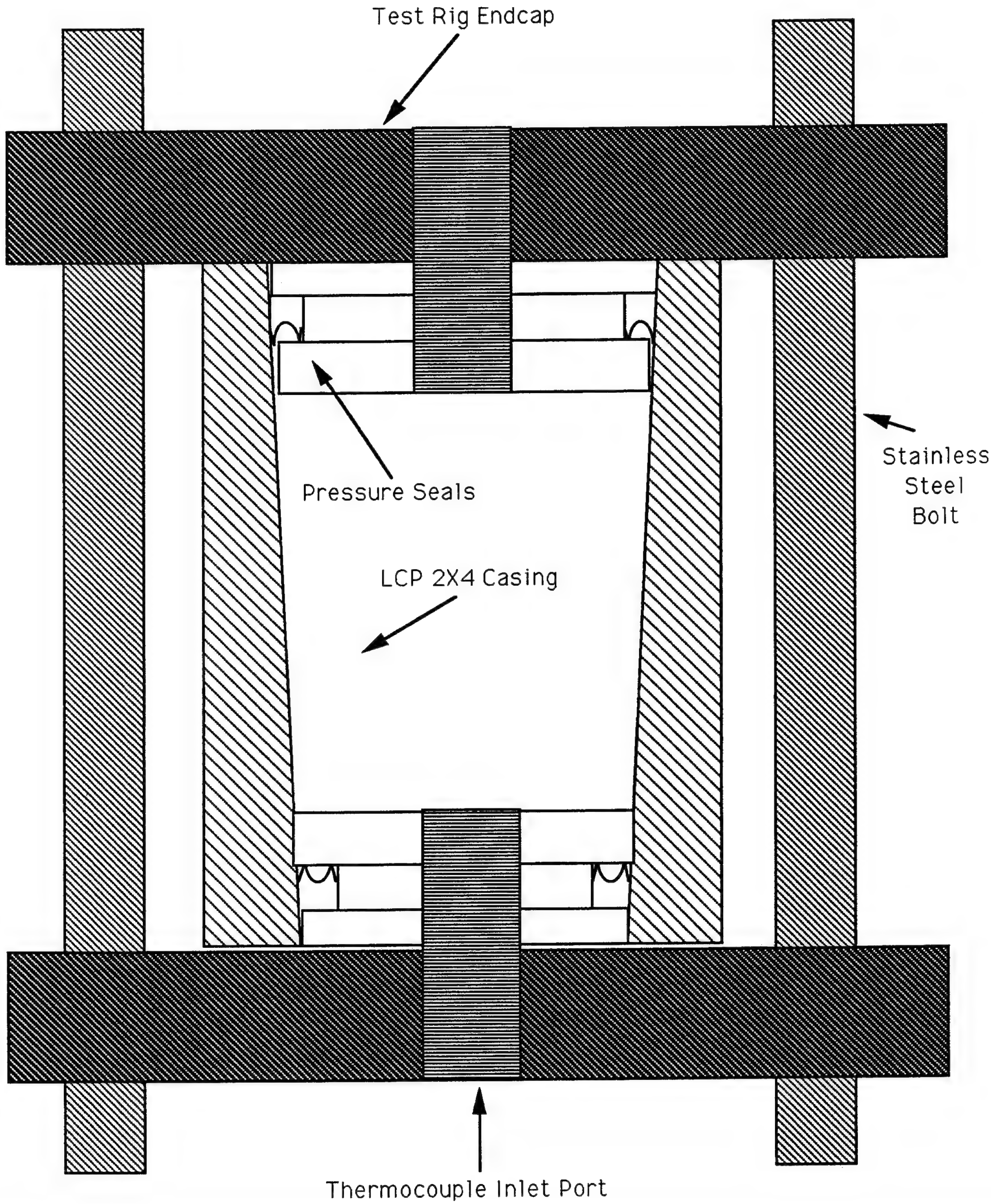
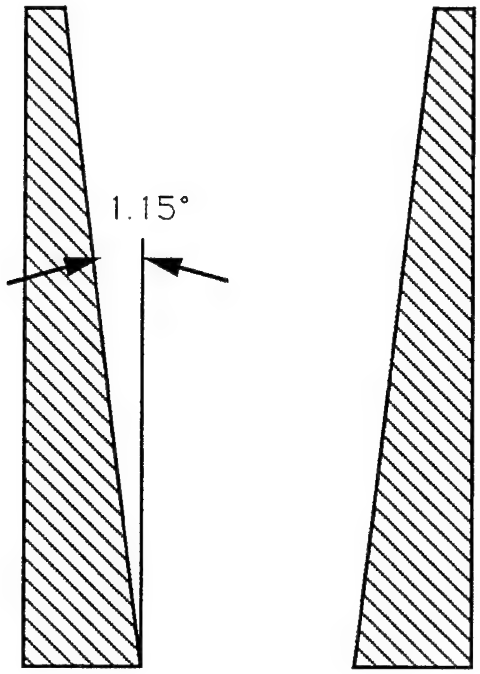

Test Rig Endcap
Pressure Seals
Stainless
Steel
Bolt
LCP 2X4 Casing
Thermocouple Inlet Port

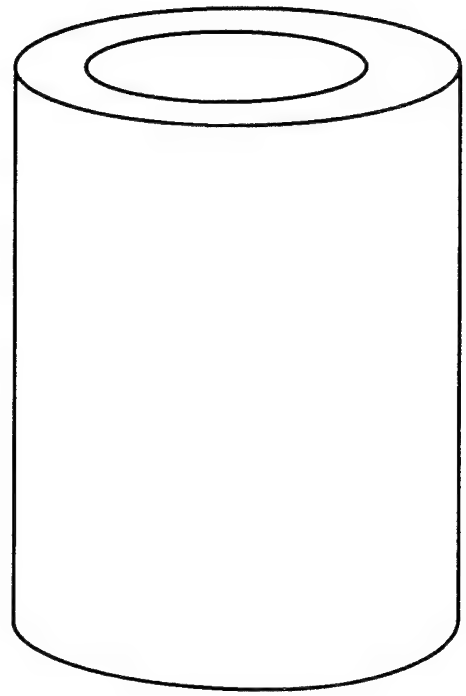
Diagram #2

Liquid Crystal Polymer 2X4 Perspectives

Cross Sectional View:



Front View



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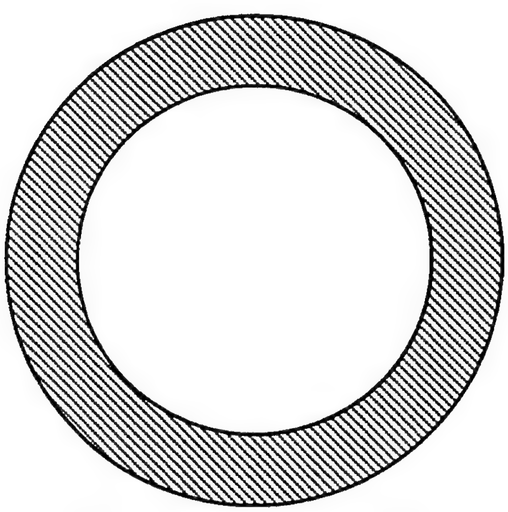

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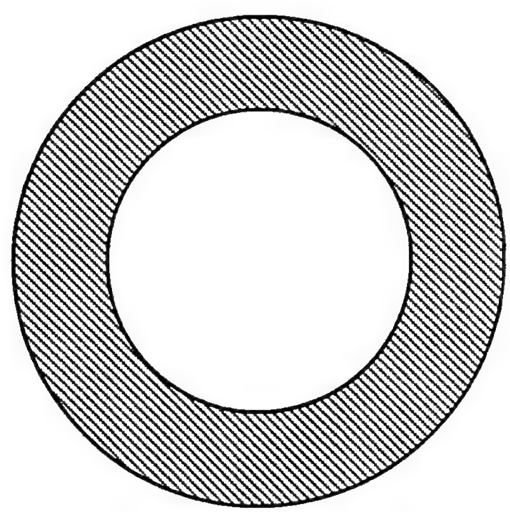
Inner Diameter: 2.2286
Outer Diameter: 2.4895

Thick End:



Average Dimensions:
Wall Thickness: 0.2095
Inner Diameter: 2.0545
Outer Diameter: 2.4895

examples of which are; liquid nitrogen (which liquefies at approximately -194° Celsius) and liquid oxygen (approximately -183° C). The ideal material would be extremely strong and light, yet capable of withstanding these cryogenic temperatures. Other factors like compatibility with cryogenic propellants must be taken into account.

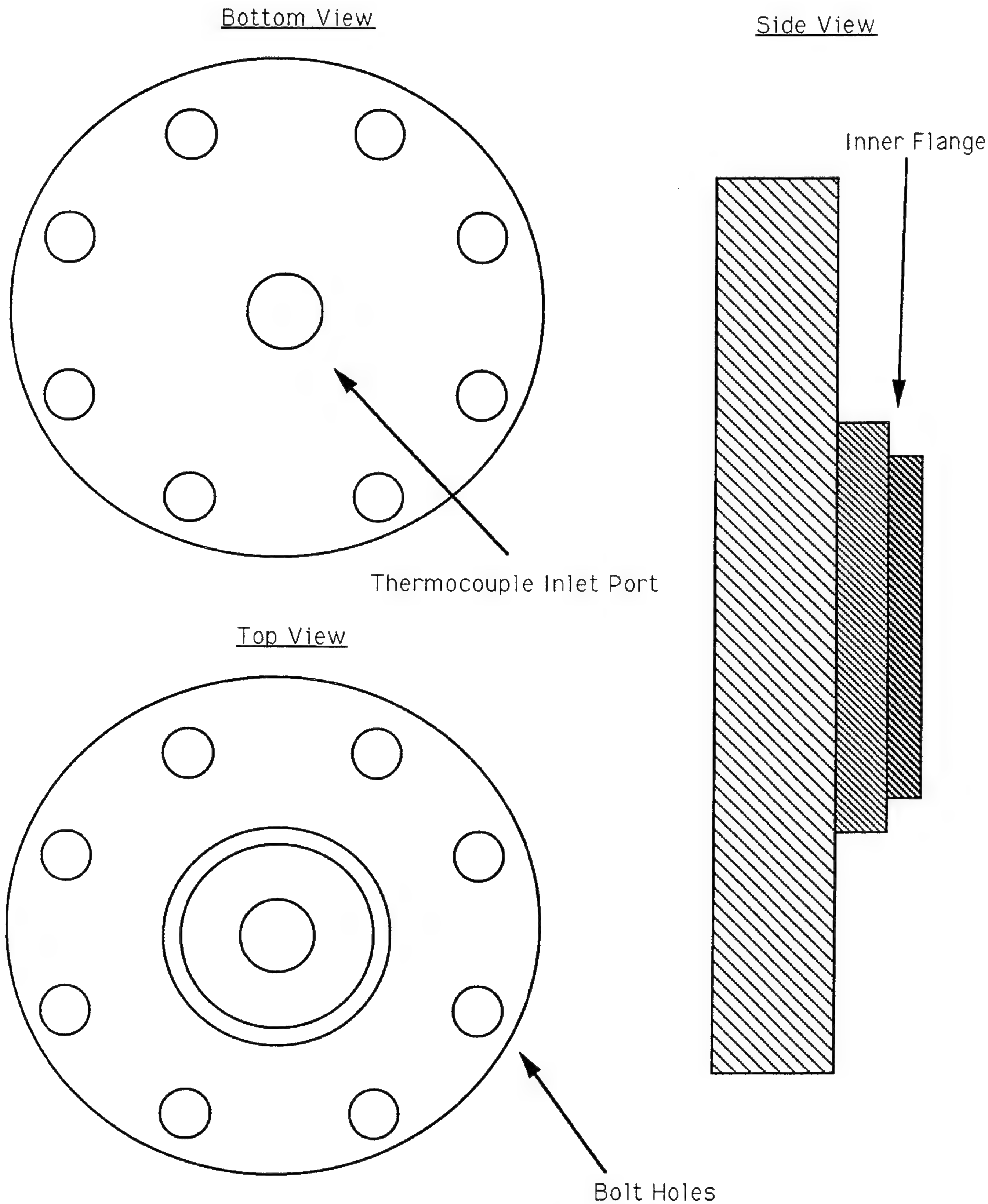
The actual testing consists of exposing various LCPs to high pressures. The idea being; to dtermine which polymer will be able to withstand the necessary pressures for operation inside a turbopump. The LCP will be tested in a specially designed test rig (See Diagram #1). The test rig is made of stainless steel. The stainless steel is of the 300 series, which is noted for its lack of embrittlement in cryogenic temperatures.

The test specimens will be injection molded into hollow right cylindrical shapes (see Diagram #2). Due to the nature of the injection molding process all the LCPs specimens will have a slight 1.15° taper. The specimens will be placed onto a specially designed test rig.

The test rig consists primarily of two end caps (see Diagram #3). These end caps go both above and below the LCP. The LCP will be fitted around the inner flange of the test rig end cap. The pressure will be retained via a pressure seal also placed around the flange. The entire structure will be held together by a set of 6 bolts, that run from one end cap to the other. The testing will utilize an on-site pressurization facility to pressurize the LCP case, using gaseous helium. The test-rig has been equipped with an inlet pressurization line and a

Diagram #3

Test Rig Endcap

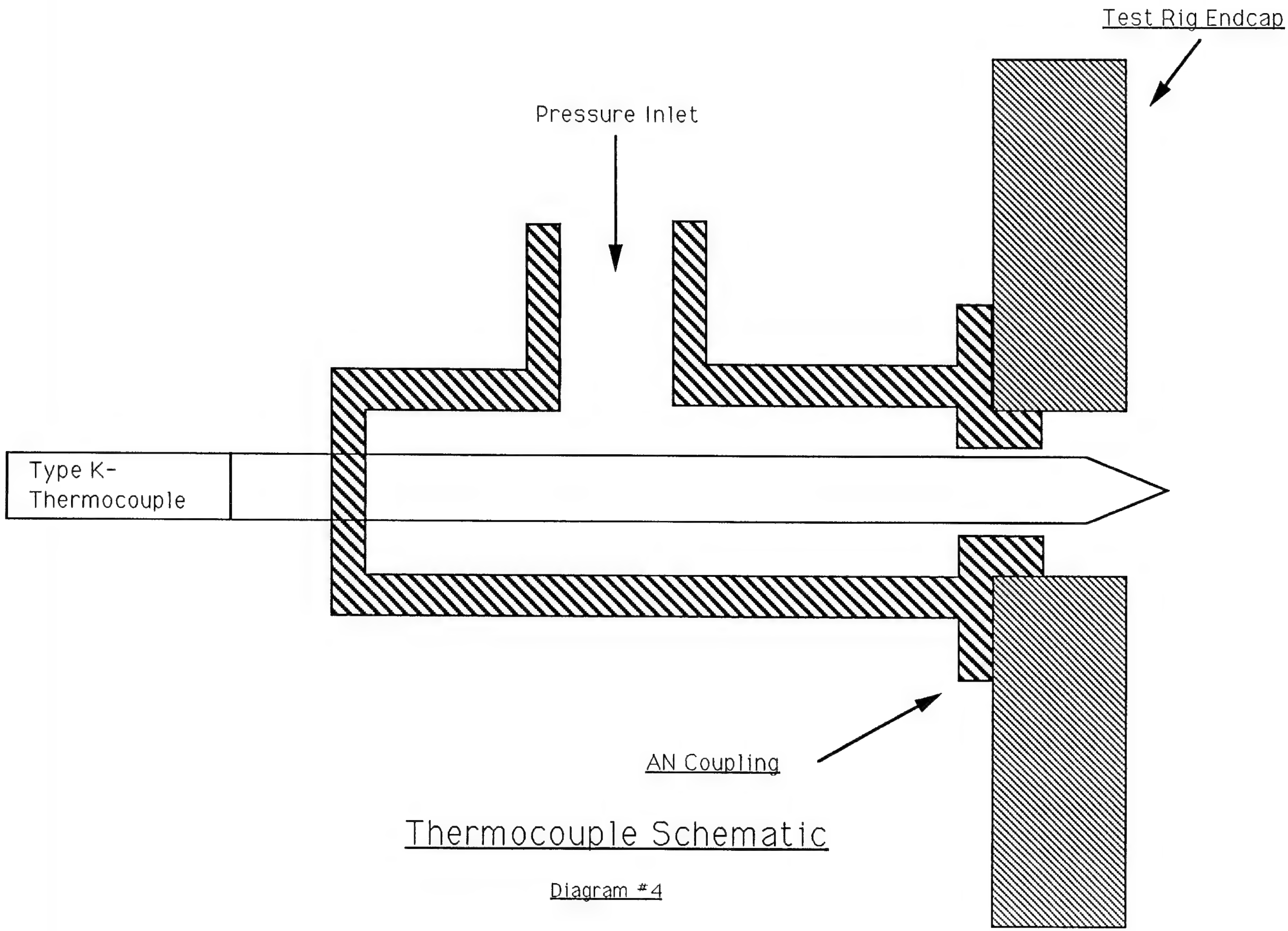


ventline. The whole device will then be placed inside a stainless steel box. This is done in order to contain both the exploding LCP specimen and the cryogenic fluid.

During the cryogenic testing the LCP will be pre-pressurized to 300 PSIG before the test rig is submerged in the cryogens. This pre-pressurization stage will assure that the seals seat properly. Also thermocouples will be installed in order to determine when the 2X4 casing has reached thermal equilibrium.

After reaching equilibrium, the pressure inside the polymer casing will be increased until the material ruptures. Testing will be done in both ambient and cryogenic environments. The cryogenic fluid will be liquid nitrogen. In this environment the LCP is expected to be significantly stronger. The maximum pressure is expected to 2000 psi, with possibilities for higher pressures should the LCP prove to be stronger than expected. The hardware is rated to 4000 psi.

A pressure transducer will be part of necessary instrumentation. A second transducer will also be in place to back-up in case of failure. The transducers will be placed upstream of the 2X4 LCP casing. All thermocouple data will be taken by two thermocouples located at one end of the test rig. The will be ported through a "T" connector (also known as an inlet/thermocouple manifold) allowing direct access to the 2X4 case. The pressure inlet and the ventline outlet will both use the other "T" port (see Diagram #4). Data acquisition will be taken to provide 100 samples a second.



Thermocouple Schematic

Diagram #4

USAF TURBOPUMP PLASTICS TESTING; OXYGEN EXPOSURE

Harold D. Beeson
Richard Shelley
NASA-White Sands Test Facility

NASA WHITE SANDS TEST FACILITY

USAF TURBO PUMP PLASTICS TESTING
SPECIAL TEST DATA REPORT

WSTF # 91-24845 to 47
October 10, 1991

1.0 TEST MATERIALS

Vectra A950 (ivory color), DuPont HX400 (green-brown), and
Xydar RC210 (beige)

Additional Information
These test materials are all liquid crystal polymers (LCP), which are described further in Appendix B. The three materials were ranked according to the results of the testing, and were also compared with Teflon polytetrafluoroethylene (PTFE) for reference, as the behavior of Teflon PTFE in oxygen environments is well-documented.

Required dimensions for the test samples were supplied by White Sands Test Facility (WSTF); molding and sample preparation were performed by Edwards Air Force Base.

2.0 TEST DOCUMENTS

JSC Form 2035 and Special Instructions (Appendix A), NASA Handbook NHB 8060.1B, and the ASTM Annual Book of Standards, 1986

3.0 TEST APPARATUS

The mechanical impact test apparatus is shown in Figure 1. The samples are placed in the cup assembly, then the electromagnet releases the plummet assembly to impact the sample. The test atmosphere is liquid oxygen (LOX). This test examines the effects of high-impact ignition sources on a material in LOX.

The Fourier Transform Infrared (FTIR) tube furnace and Differential Scanning Calorimeter (DSC)/light pipe assembly are shown in Figures 2 and 3. To use the FTIR tube furnace, the sample is placed inside the tube furnace. Oxygen is flowed over the sample, then analyzed with a Fourier Transform Infrared (FTIR) spectrometer for gaseous emissions. The DSC/light pipe assembly is a silicon photodiode attached via a light pipe to a DSC chamber. To use the DSC/light pipe assembly, the sample is placed inside the chamber, and the temperature is raised slowly until the sample ignites. The silicon photodiode then detects radiative flame emissions from the sample. Both tests examine the effect of temperature on the ignition properties of materials. The purpose is to determine at what temperature gaseous emissions, ignition, or other events occur.

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Figure 4 shows a promoted combustion chamber similar to the one used in this testing. The promoted combustion test apparatus provides a known volume and atmosphere for a combustion test. It consists of a chamber in which the sample is placed in a sample holder. An igniter is then placed at the top of the sample. This test examines the combustion properties of materials in oxygen.

4.0 TEST APPROACH

Three types of test were conducted: mechanical impact, autoignition temperature testing, and promoted combustion testing.

4.1 MECHANICAL IMPACT TESTING

Mechanical impact testing was performed according to NHB 8060.1B, Test 13A, and ASTM D2512. The samples were 1.75-cm-diameter, 0.15-cm-thick disks. A test consisted of 20 open-cup, ambient-pressure impacts of 98 J in liquid oxygen (LOX). A reaction was considered to have occurred when a flash, an audible report, or sample charring occurred.

4.2 AUTOIGNITION TEMPERATURE TESTING

Autoignition temperature testing is defined as the temperature at which the sample will spontaneously ignite. Autoignition testing was performed with the FTIR tube furnace apparatus and with the Differential Scanning Calorimeter (DSC)/light pipe apparatus; both tests were in gaseous oxygen (GOX). The testing performed with the FTIR tube furnace was recorded on video.

The FTIR apparatus gave autoignition temperature (AIT) at ambient pressure, precombustion gases, and gases given off during and after combustion.

The DSC apparatus gave ignition temperatures. The light pipe measured AIT light emission at ambient pressure. The DSC was operated at a heating rate of 10 °C per minute in a GOX environment (150 gccm).

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4.3 PROMOTED COMBUSTION TESTING

The method used for the promoted combustion testing was similar to that used for promoted combustion of metals.[1] The differences were that oxygen pressures were lower in this testing, propagation of the burn was downward, and the chamber had a capacity of 120 liters and was designed for low-pressure (up to 120 kPa). The size of the chamber was such that sufficient oxygen was available for complete combustion of the sample at the lowest test pressure. The oxygen pressure range used in this testing was 2.1 kPa to 120 kPa. The promotor was nichrome wire, placed at the top of the sample for downward flame propagation in GOX. The promotor was heated by an electrical current providing a constant source of energy. Samples were 0.32-cm-diameter, 7.62-cm-long rods. Sample burning was recorded through a chamber view port by video.

5.0 TEST RESULTS

Results of mechanical impact, autoignition temperature (both with the FTIR tube furnace and the DSC/light pipe), and promoted combustion testing follow. The materials are listed in the tables according to their ranking; the ones ranking best are listed first.

5.1 MECHANICAL IMPACT TESTING

Table 1 shows the results of the mechanical impact testing.

---

[1] Steinberg, T. A., M. A. Rucker, and H. D. Beeson. "Promoted Combustion of Nine Structural Metals in High Pressure Gaseous Oxygen: A Comparison of Ranking Methods." Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fourth Volume, ASTM STP 1040, Edited by J. M. Stoltzfus, F. J. Benz, and J. S. Stradling, American Society for Testing and Materials, Philadelphia, 1989, pp. 54-75.

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Table 1. Reactions in 20 Tests

MATERIAL	REACTIONS
Vectra A950	3
DuPont HX400	18
Xydar RC210	19

5.2 AUTOIGNITION TEMPERATURE TESTING

The results of the FTIR Tube Furnace testing are shown in Table 2. The tests were recorded on Video 715A.

None of the three materials showed ignition with the DSC/light pipe, but large exotherms were detected for each. Exotherm values (not AIT values) for each material are in Table 3.

An endotherm was exhibited by DuPont HX400 with a peak at 306 °C; this may correspond to melting. Figures 5, 6, and 7 show DSC test results. The samples were tested up to 600 °C in the DSC/light pipe, but the traces were cut off at the point after which the data remained constant, typically between 450 and 500 °C.

Table 2. Results of FTIR Tube Furnace Testing

MATERIAL	AIT °C	CO_2 EMISSION TEMP °C	GASEOUS EMISSION TYPES
Xydar RC210	542	305	CO_2, CO, H_2O, aromatic hydrocarbons, and esters
Vectra A950	540	320	CO_2, CO, aromatic hydrocarbons and esters
DuPont HX400	505	275	CO_2, CO, aromatic hydrocarbons and esters

Table 3. Results of DSC/Light Pipe Testing

Material	Exotherm Temperature °C
Vectra A950	473
Xydar RC210	470
DuPont HX400	370

5.3 PROMOTED COMBUSTION TESTING

The tests were recorded on Video 10430A. The threshold pressure is defined here as the pressure above which the sample will burn. A burn was considered sustained combustion of at least 5.1 cm of the sample, which allowed for combustion beyond igniter effects and before heat sinking effects from the sample holder. Burn rates were also calculated as the rate of propagation of the flame front.

Threshold pressures for the Xydar RC210, Vectra A950, and DuPont HX400 were 8.3 kPa, 6.6 kPa, and 3.5 kPa respectively. Threshold pressures are indicated in Figure 8. Burn rate comparisons are given in Figure 9. Teflon PTFE had a threshold pressure of 110 kPa (reported here for comparison purposes). Teflon PTFE burned at a much slower rate (0.014 cm/sec at 110 kPa), and is not shown on the comparison.

6. 0 DISCUSSION

A material is considered more suitable for use in oxygen if it shows fewer reactions when tested by mechanical impact, has a higher AIT, and has a higher threshold pressure and a lower burn rate.[2]

Another important consideration when determining the suitability of polymers for oxygen service is the degradation products. Polymers with non-oxidizable products tend to be surface burners, as shown in the promoted combustion video of Teflon PTFE; the significance of this is

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2 "Standard Guide for Evaluating Nonmetallic Materials for Oxygen Service." ASTM G63, American Society for Testing Materials, Philadelphia, 1983.

that surface burners tend to burn with lower flame temperatures as calculated by the Gordon-McBride computer program.[3] Materials with lower flame temperatures are less likely to ignite surrounding materials. CO_2 emission temperature is an indication of when degradation products of the polymer begin evolving; the lower this temperature is, the more likely the polymer is to ignite.

Vectra A950 had the least number of mechanical impact reactions of the three tested materials. Both DuPont HX400 and Xydar RC210 showed high susceptibilities to reactions by mechanical impact. Teflon PTFE usually shows no reactions under the given mechanical impact test conditions.[4]

All three materials had high AIT values. Vectra A950 and Xydar RC210 had similar AIT values, higher than that for Teflon PTFE (525 °C).[5] The DuPont HX400 had a lower AIT than the Teflon PTFE.

The exotherm values from DSC testing showed similar trends to the AIT temperatures from the FTIR tube furnace testing. The DSC testing also showed that DuPont HX400 undergoes an endotherm at around 275 °C; it may have been melting.

Gaseous emissions from the test materials were CO_2, CO, aromatic hydrocarbons, and esters (H_2O was also emitted from Xydar RC210). The

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3 Gordon, S., and B. J. McBride. "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations." NASA SP-273, National Aeronautics and Space Administrations, Washington, DC, 1971.

4 Moffett, G. E., N. E. Schmidt, M. D. Pedley, and L. J. Linley. "An Evaluation of the Liquid Oxygen Mechanical Impact Test." Symposium on Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fourth Volume, ASTM STP 1040, Edited by J. M. Stoltzfus, F. J. Benz, and J. S. Stradling, American Society for Testing and Materials, Philadelphia, 1989.

5 Tapphorn, R. M., R. Shelley, and F. J. Benz. "Test Developments for Polymers in Oxygen-Enriched Environments." Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fifth Volume, ASTM STP 1111, Edited by J. M. Stoltzfus and K. McIlroy, American Society for Testing and Materials, Philadelphia, 1991.

aromatic groups can be considered as oxidizable fuel. Other products given off by Teflon PTFE are CO, COF_2, and CF_4; these products are not easily oxidizable.[5] The test materials producing oxidizable groups were gaseous burners and burned with flames (also shown in the promoted combustion video).

Vectra A950 was most similar to Teflon PTFE in that the CO_2 emission temperature was high; emission of CO_2 from Teflon PTFE is usually observed between 350 and 400 °C.[5]

All three polymers had low threshold pressures compared with that of Teflon PTFE. Vectra A950 had the lowest burning rate of the three materials in the pressure range tested, but its burning rate values were much higher than those of Teflon PTFE.

Vectra A950 had the overall best properties. It ranked best in all the tests except autoignition temperature testing, where it was about the same as Xydar RC210. DuPont HX400 ranked the overall poorest of the three materials.

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5 Tapphorn, R. M., R. Shelley, and F. J. Benz. "Test Developments for Polymers in Oxygen-Enriched Environments." Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fifth Volume, ASTM STP 1111, Edited by J. M. Stoltzfus and K. McIlroy, American Society for Testing and Materials, Philadelphia, 1991.

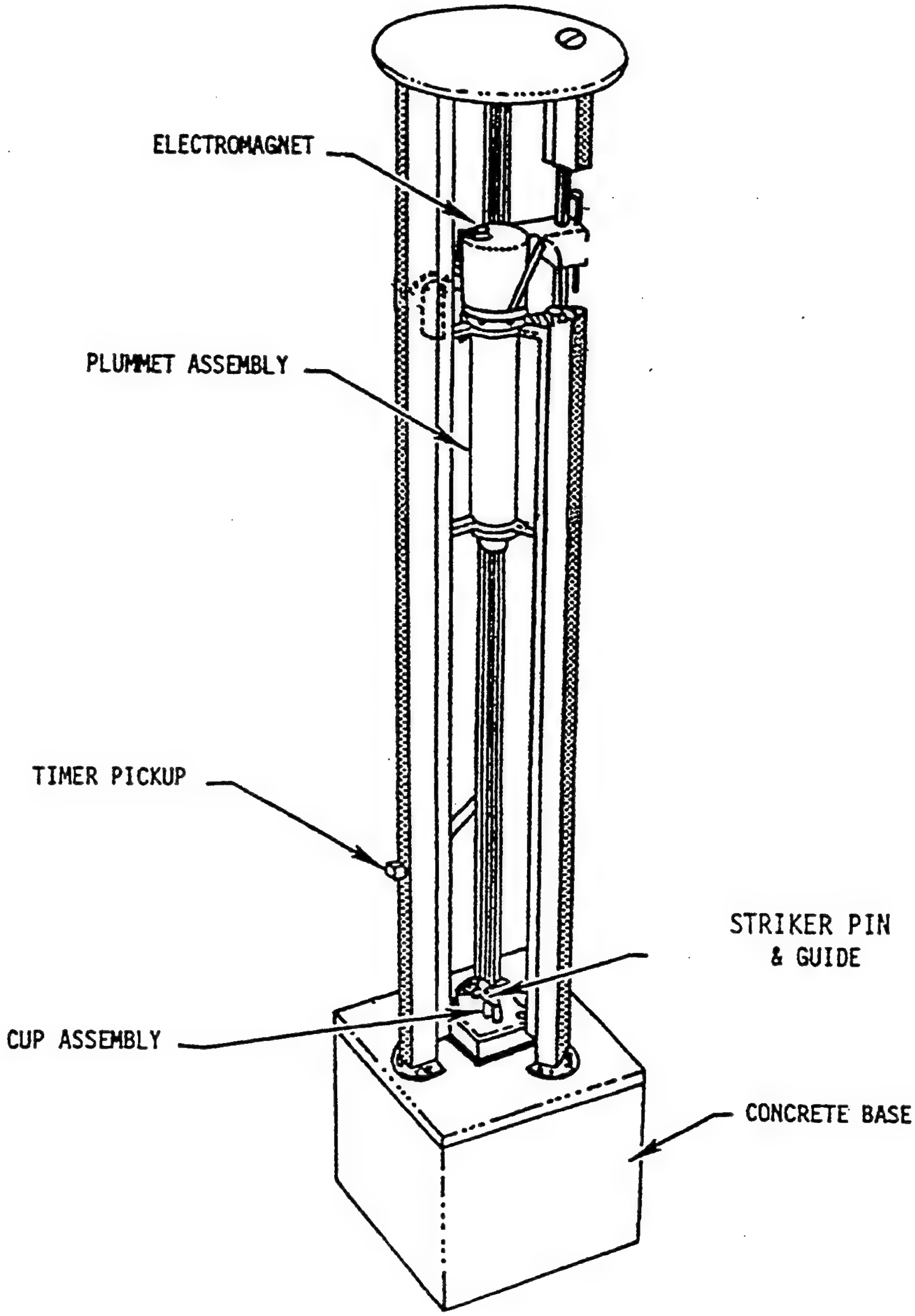

Figure 1. Mechanical Impact Testing Apparatus

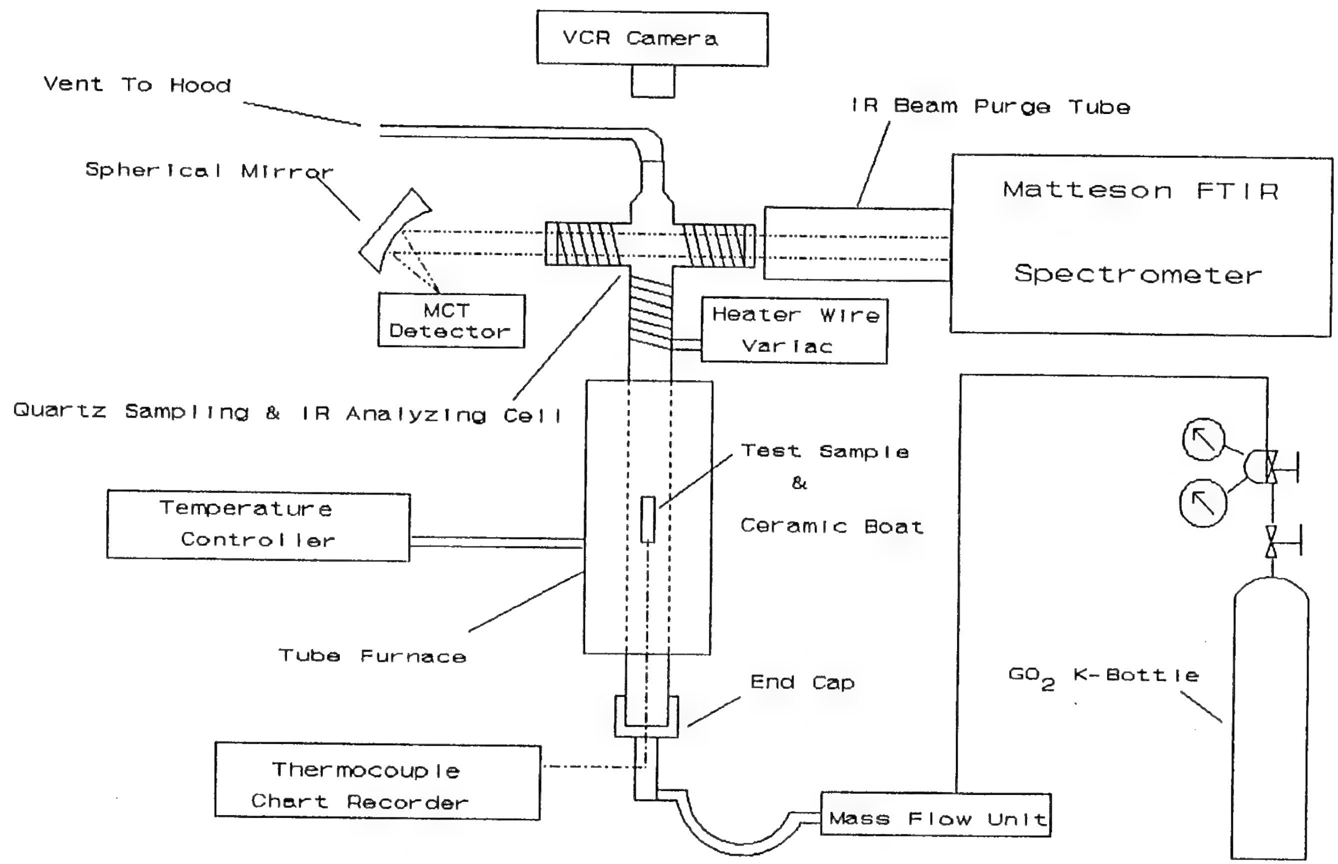

Figure 2. FTIR Tube Furnace

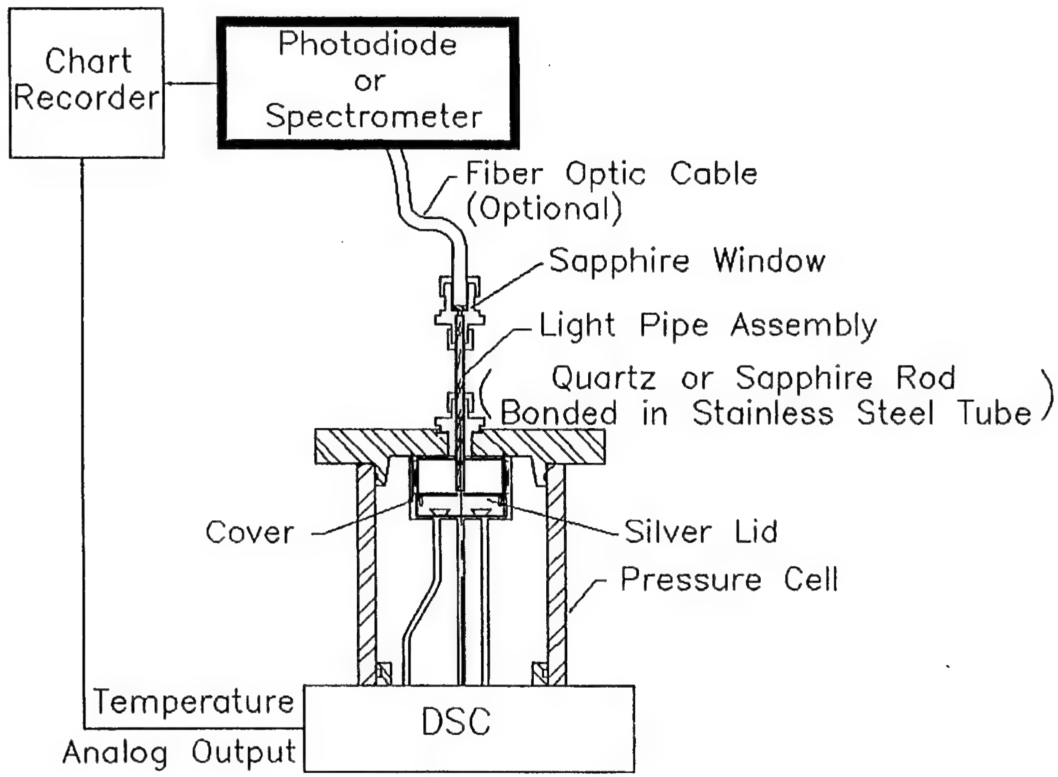

Figure 3. DSC/Light Pipe Assembly

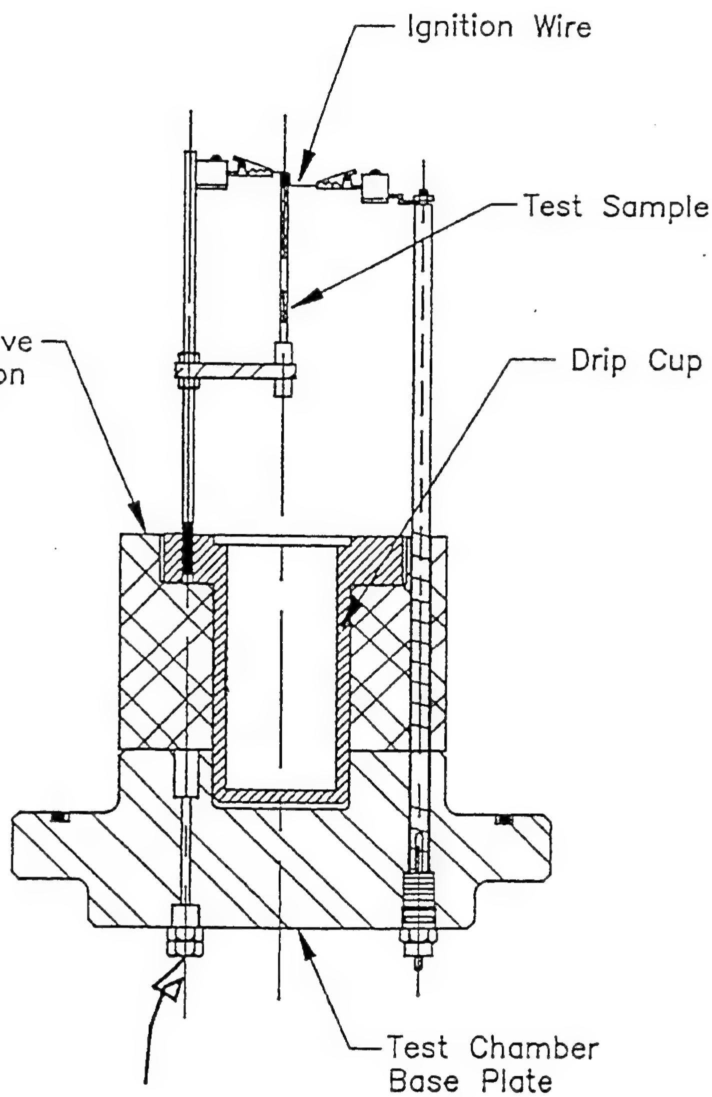

Figure 4. Promoted Combustion Test Apparatus

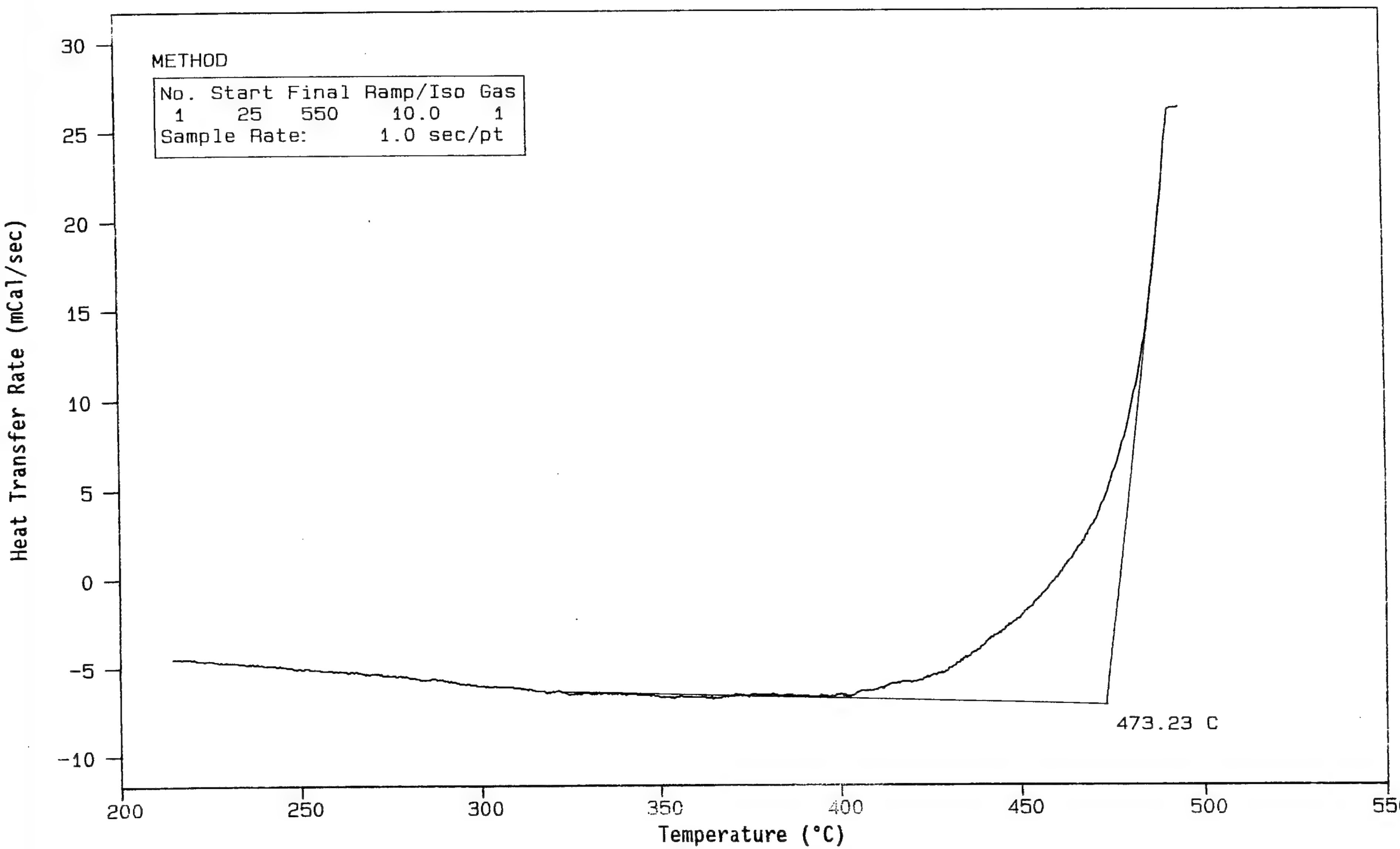

Figure 5. Vectra A950 DSC Trace

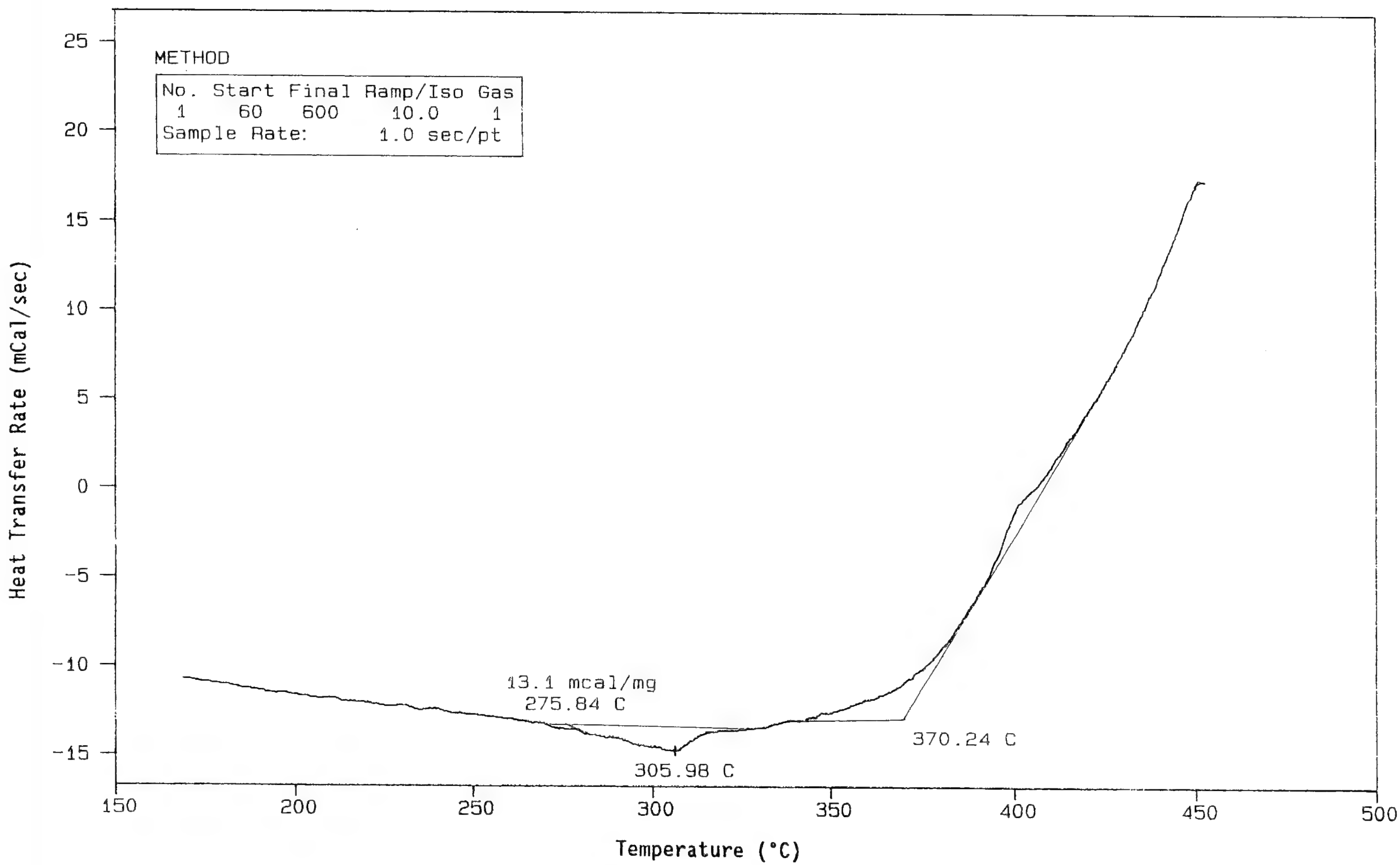

Figure 6. DuPont HX400 DSC Trace

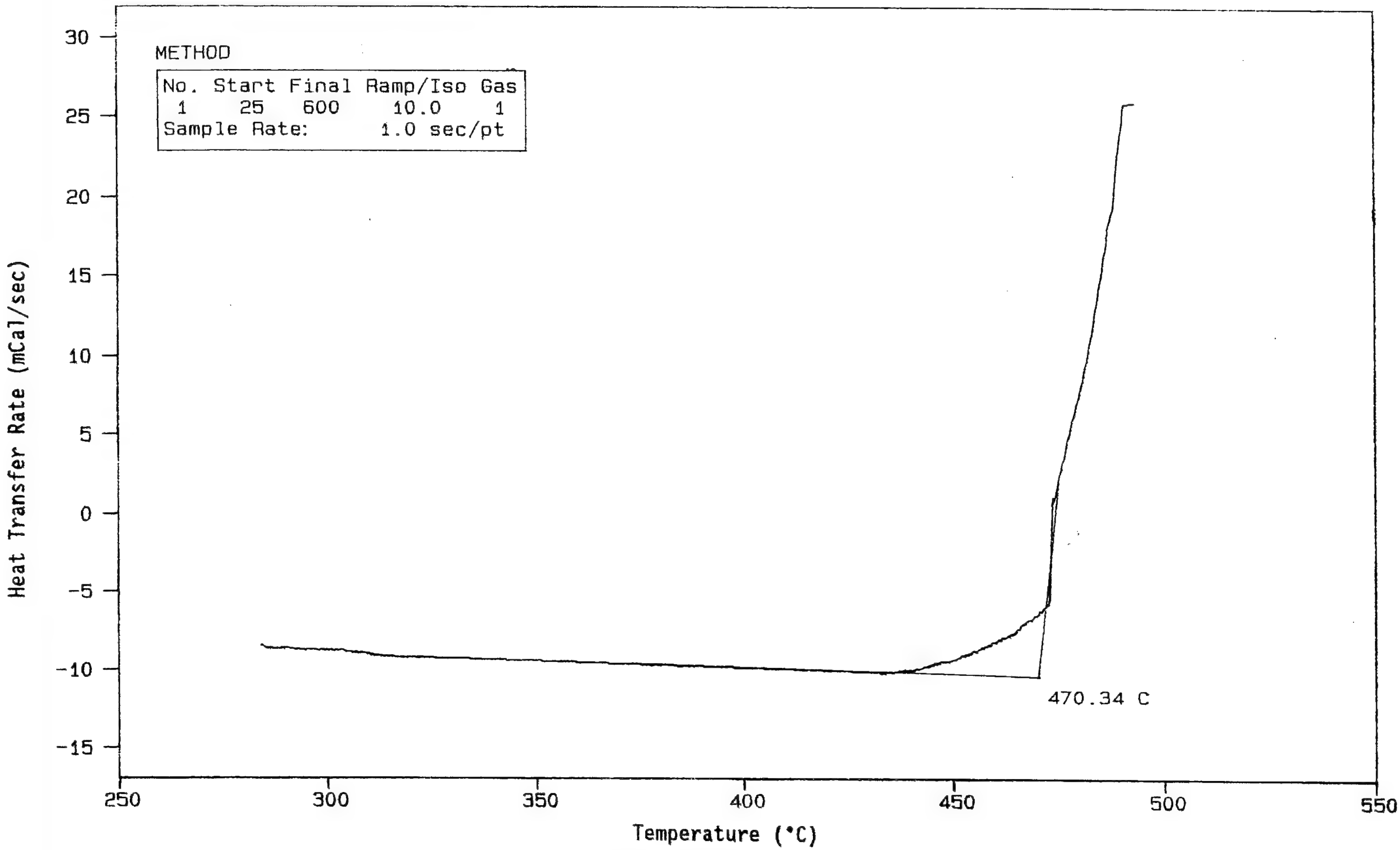

Figure 7. Xydar RC210 DSC Trace

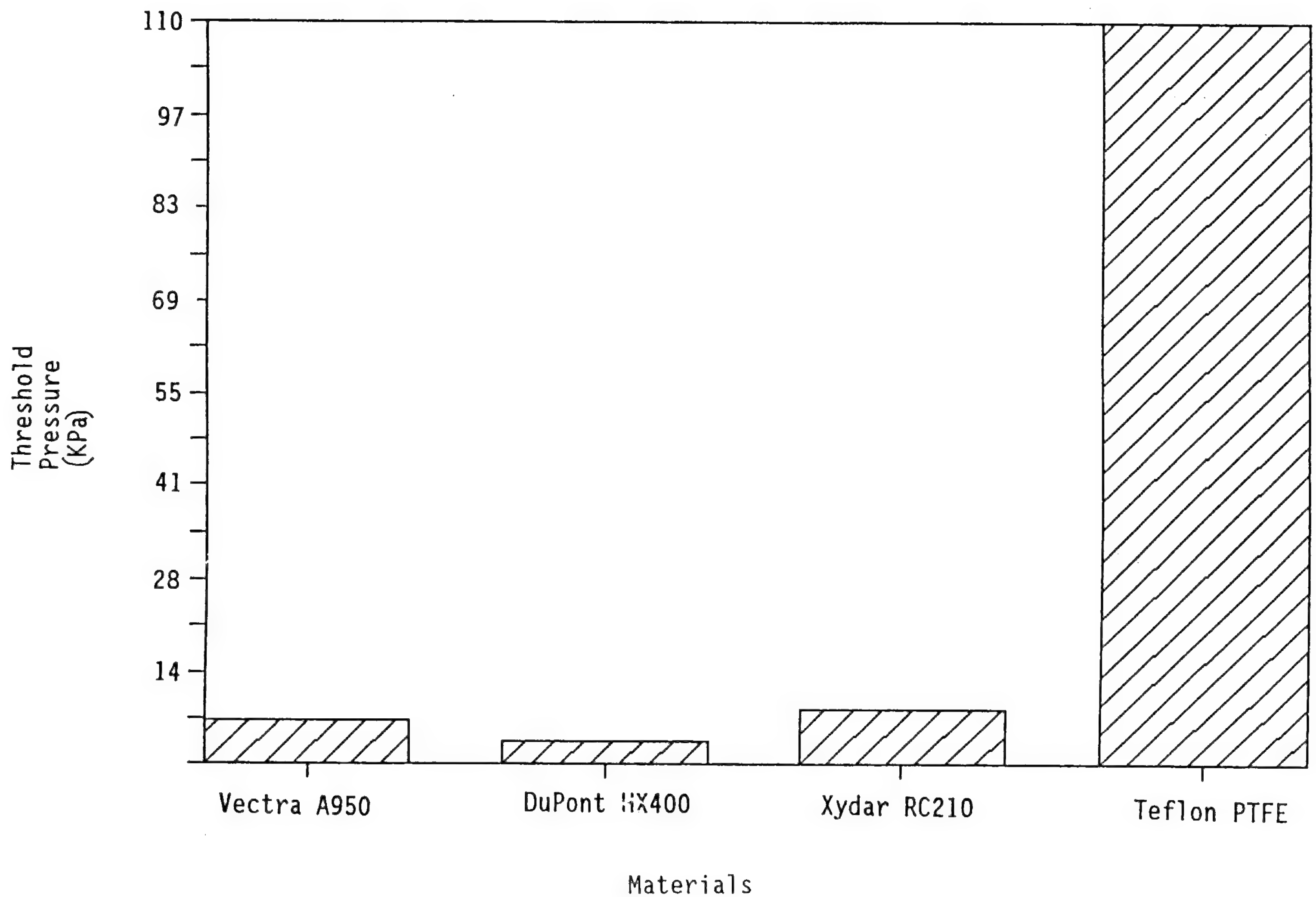

Figure 8. Threshold Pressure Comparison
Vectra A950, DuPont HX400, Xydar RC210, and Teflon

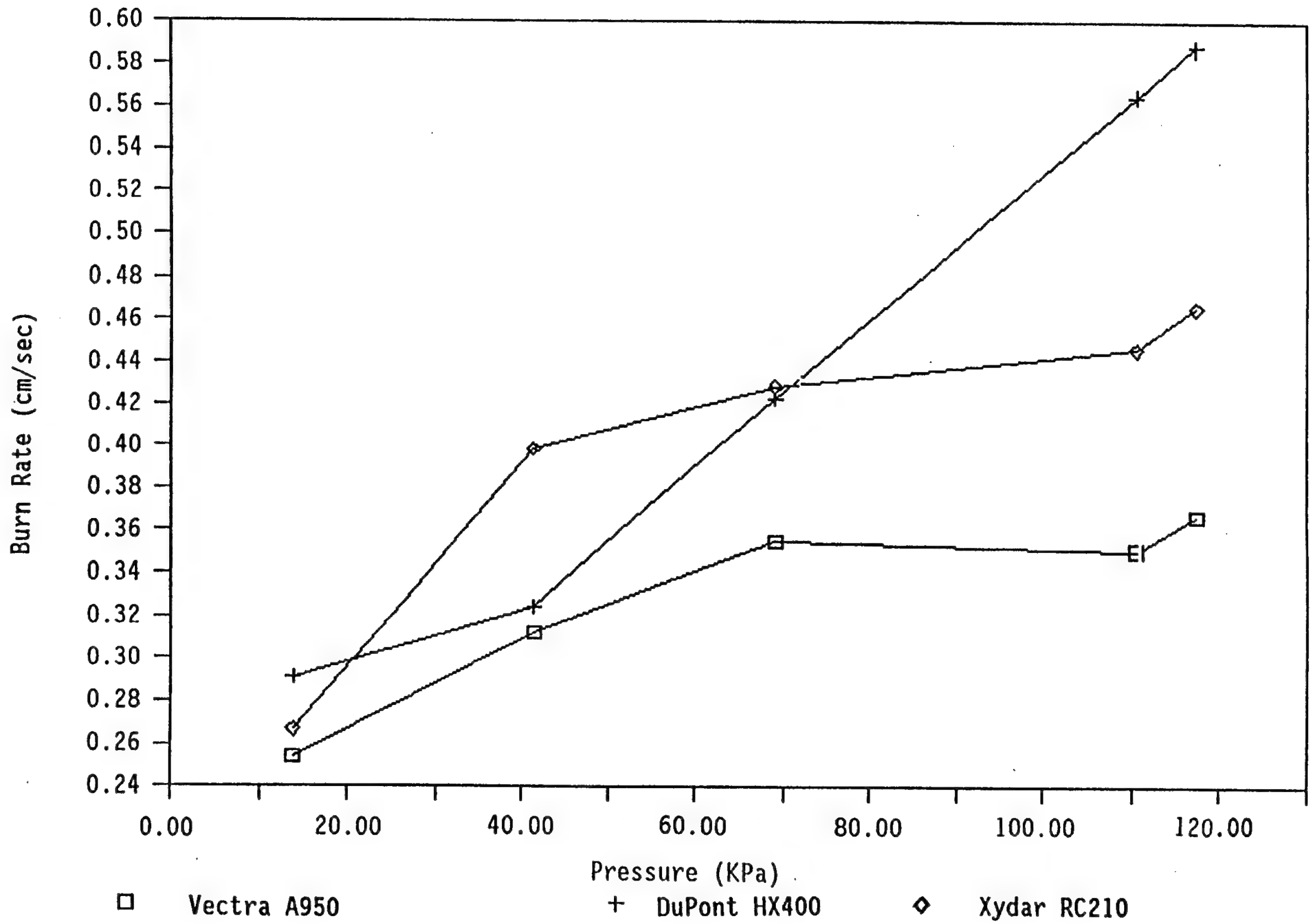

Figure 9. Burn Rates in Oxygen for Vectra A950, DuPont HX400, Xydar RC210

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Prepared by: Richard Shelley

Richard Shelley
Lockheed-ESC

Reviewed by: Harold Beeson

Harold Beeson
NASA

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October 10, 1991

APPENDIX A

OFFICE USE ONLY

TEST FACILITY I.D. NUMBER: 91-24845

COORDINATOR: HB

REQUEST NO.: WSTF

TEST FACILITY: WSTF

CODE:

NASA JSC TEST REQUEST

NOTE TO TEST FACILITY: A COPY OF THIS REQUEST SHOULD BE RETURNED WITH THE TEST REPORT.

NAME: Harold Beeson/Richard Shelley

ORGANIZATION: NASA/LESC

ADDRESS: Building 200
NASA/JSC/WSTF
P.O. Drawer MM, Las Cruces, NM 88004

DATE: March 27, 1991

PHONE: 505-524-5687

1. MANUFACTURER'S IDENTIFICATION (ITEM DESCRIPTION): Vectra A950 (Ivory color)

2. MANUFACTURER'S NAME: Hoechst Celanese

3. SPECIFICATION: 80 mech. imp. discs
80 prom ign. rods

4. CHEMICAL CLASS: Liquid Crystal Polymer

5. GENERIC USE: Oxygen testing

6. CHECK CATEGORY NHB8060.1: ☐ A ☐ B ☐ C ☐ D ☐ E ☐ F ☐ G ☐ H ☐ J

7. TEST REQUIRED NHB8060.1: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10 ☐ 11 ☐ 12 ☐ 13 ☐ 14 ☐ 15 ☐ 16 ☐ VCM ☐ TOCM ☒ SPECIAL

8. VEHICLE: N/A

9. PART NUMBER & SERIAL NO.: N/A

10. PROJECT: Plastics Turbo Pump-USAF

11. USE TEMPERATURE: N/A

12. USE ATMOSPHERE/FLUID: N/A

13. IGNITER TYPE: N/A

14. USE PRESSURE: N/A

15. USE THICKNESS: N/A

16. INTENDED APPLICATION: Test material for oxygen testing

17. QUANTITY IN HABITABLE AREA/HAZARDOUS FLUID/VACUUM: N/A

18. CURE TIME: N/A

19. CURE TEMPERATURE: N/A

20. CURE PRESSURE: N/A

21. TEST ARTICLE: N/A

22. TEST ARTICLE AREA: N/A

23. NUMBER ITEMS TESTED: N/A

24. NUMBER ITEMS TO BE FLOWN: N/A

25. TEST CHAMBER VOLUME: N/A

26. TEST CHAMBER ATMOSPHERE: N/A

27. TEST CHAMBER PRESSURE: N/A

28. TEST CHAMBER TEMPERATURE: N/A

29. TEST CHAMBER DURATION: N/A

30. CLEANING SPEC: N/A

31. MATL CODE: N/A

32. PHOTOGRAPHIC COVERAGE: ☒ VIDEO VHS-VCR ☐ STILLS ☐ NONE

33. SPECIAL INSTRUCTIONS

1. Perform mechanical impact testing per NHB 8060.1B, Test 13A.
2. Perform autoignition temperature testing in GOX.
3. Perform promoted combustion testing in GOX at threshold pressure and burn rate.

NASA JSC TEST REQUEST

NOTE TO TEST FACILITY: A COPY OF THIS REQUEST SHOULD BE RETURNED WITH THE TEST REPORT.

OFFICE USE ONLY	
TEST FACILITY I.D. NUMBER	91-24846
COORDINATOR	HB
REQUEST NO.	WSTF
TEST FACILITY	WSTF
CODE	

NAME: Harold Beeson/Richard Shelley

ORGANIZATION: NASA/LESC

ADDRESS: Building 200
NASA/JSC/WSTF
P.O. Drawer MM, Las Cruces, NM 88004

DATE: March 27, 1991

PHONE: 505-524-5687

1. MANUFACTURER'S IDENTIFICATION (ITEM DESCRIPTION): DuPont HX400 (green-brown)
2. MANUFACTURER'S NAME: Du Pont
3. SPECIFICATION: 80 mech. imp. discs; 80 prom ign. rods
4. CHEMICAL CLASS: Liquid Crystal Polymer
5. GENERIC USE: Oxygen testing
6. CHECK CATEGORY NHB8060.1: ☐ A ☐ B ☐ C ☐ D ☐ E ☐ F ☐ G ☐ H ☐ J
7. TEST REQUIRED NHB8060.1: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10 ☐ 11 ☐ 12 ☐ 13 ☐ 14 ☐ 15 ☐ 16 ☐ VCM ☐ TOCM ☒ SPECIAL
8. VEHICLE: N/A
9. PART NUMBER & SERIAL NO.: N/A
10. PROJECT: Plastics Turbo Pump-USAF
11. USE TEMPERATURE: N/A
12. USE ATMOSPHERE/FLUID: N/A
13. IGNITER TYPE: N/A
14. USE PRESSURE: N/A
15. USE THICKNESS: N/A
16. INTENDED APPLICATION: Test material for oxygen testing
17. QUANTITY IN HABITABLE AREA/HAZARDOUS FLUID/VACUUM: N/A
18. CURE TIME: N/A
19. CURE TEMPERATURE: N/A
20. CURE PRESSURE: N/A
21. TEST ARTICLE: N/A
22. TEST ARTICLE AREA: N/A
23. NUMBER ITEMS TESTED: N/A
24. NUMBER ITEMS TO BE FLOWN: N/A
25. TEST CHAMBER VOLUME: N/A
26. TEST CHAMBER ATMOSPHERE: N/A
27. TEST CHAMBER PRESSURE: N/A
28. TEST CHAMBER TEMPERATURE: N/A
29. TEST CHAMBER DURATION: N/A
30. CLEANING SPEC: N/A
31. MATL CODE: N/A
32. PHOTOGRAPHIC COVERAGE: ☒ VIDEO VHS-VCR ☐ STILLS ☐ NONE

33. SPECIAL INSTRUCTIONS

1. Perform mechanical impact testing per NHB 8060.1B, Test 13A.
2. Perform autoignition temperature testing in GOX.
3. Perform promoted combustion testing in GOX at threshold pressure and burn rate.

NASA JSC TEST REQUEST

NOTE TO TEST FACILITY: A COPY OF THIS REQUEST SHOULD BE RETURNED WITH THE TEST REPORT.

OFFICE USE ONLY	
TEST FACILITY I.D. NUMBER	91-24847
COORDINATOR	HB
REQUEST NO.	WSTF
TEST FACILITY	WSTF
CODE	

NAME: Harold Beeson/Richard Shelley

ORGANIZATION: NASA/LESC

ADDRESS: Building 200
NASA/JSC/WSTF
P.O. Drawer MM, Las Cruces, NM 88004

DATE: March 27, 1991

PHONE: 505-524-5687

1. MANUFACTURER'S IDENTIFICATION (ITEM DESCRIPTION): Xydar RC210 (beige)

2. MANUFACTURER'S NAME: Amsco

3. SPECIFICATION: 80 mech. imp. discs; 80 prom ign. samples

4. CHEMICAL CLASS: Liquid Crystal Polymer

5. GENERIC USE: Oxygen testing

6. CHECK CATEGORY NHB8060.1: ☐ A ☐ B ☐ C ☐ D ☐ E ☐ F ☐ G ☐ H ☐ J

7. TEST REQUIRED NHB8060.1: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10 ☐ 11 ☐ 12 ☐ 13 ☐ 14 ☐ 15 ☐ 16 ☐ VCM ☐ TOCM ☒ SPECIAL

8. VEHICLE: N/A

9. PART NUMBER & SERIAL NO.: N/A

10. PROJECT: Plastics Turbo Pump-USAF

11. USE TEMPERATURE: N/A

12. USE ATMOSPHERE/FLUID: N/A

13. IGNITER TYPE: N/A

14. USE PRESSURE: N/A

15. USE THICKNESS: N/A

16. INTENDED APPLICATION: Test material for oxygen testing

17. QUANTITY IN HABITABLE AREA/HAZARDOUS FLUID/VACUUM: N/A

18. CURE TIME: N/A

19. CURE TEMPERATURE: N/A

20. CURE PRESSURE: N/A

21. TEST ARTICLE: N/A

22. TEST ARTICLE AREA: N/A

23. NUMBER ITEMS TESTED: N/A

24. NUMBER ITEMS TO BE FLOWN: N/A

25. TEST CHAMBER VOLUME: N/A

26. TEST CHAMBER ATMOSPHERE: N/A

27. TEST CHAMBER PRESSURE: N/A

28. TEST CHAMBER TEMPERATURE: N/A

29. TEST CHAMBER DURATION: N/A

30. CLEANING SPEC: N/A

31. MATL CODE: N/A

32. PHOTOGRAPHIC COVERAGE: ☐ VIDEO VHS-VCR ☐ STILLS ☐ NONE

33. SPECIAL INSTRUCTIONS

1. Perform mechanical impact testing per NHB 8060.1B, Test 13A.
2. Perform autoignition temperature testing in GOX.
3. Perform promoted combustion testing in GOX at threshold pressure and burn rate.

JSC Form 1035 (Jan 85)

AUTHORIZATIONS, SPECIAL INSTRUCTIONS, AND NOTES

FROM	DATE	INSTRUCTIONS
Richard Shelley, WSTF	04/03/91	Perform 20 impacts in ambient LOX at 72 ft-lb regardless of the number of reactions detected.
WSTF	--	The samples have casting marks on one side.
Richard Shelley, WSTF	04/10/91	Impact the unmarked side.
WSTF	--	The results of testing will be reported in a Special Test Data Report under this WSTF Number.

AUTHORIZATIONS, SPECIAL INSTRUCTIONS, AND NOTES

FROM	DATE	INSTRUCTIONS
Richard Shelley, WSTF	04/02/91	Perform 20 impacts in ambient LOX at 72 ft-lb regardless of the number of reactions detected.
WSTF	--	The samples have casting marks on one side.
Richard Shelley, WSTF	04/10/91	Impact the unmarked side. Perform an impact on a blank disc after every fifth reaction rather than after each reaction.
WSTF	--	The results of testing will be reported in a Special Test Data Report under this WSTF Number.

AUTHORIZATIONS, SPECIAL INSTRUCTIONS, AND NOTES

FROM	DATE	INSTRUCTIONS
Richard Shelley, WSTF	04/03/91	Perform 20 impacts in ambient LOX at 72 ft-lb regardless of the number of reactions detected.
WSTF	--	The samples have casting marks on one side.
Richard Shelley, WSTF	04/10/91	Impact the unmarked side. Perform an impact on a blank disc after every fifth reaction rather than after each reaction.
WSTF	--	The results of testing will be reported in a Special Test Data Report under this WSTF Number.

NASA WHITE SANDS TEST FACILITY

USAF TURBO PUMP PLASTICS TESTING
SPECIAL TEST DATA REPORT

WSTF # 91-24845 to 47
October 10, 1991

APPENDIX B

LIQUID CRYSTAL POLYMERS

NASA WHITE SANDS TEST FACILITY

USAF TURBO PUMP PLASTICS TESTING
SPECIAL TEST DATA REPORT

WSTF # 91-24845 to 47
October 10, 1991

LIQUID CRYSTAL POLYMERS

Liquid Crystal Polymers (LCP) are rigid, rod-like polymers that exhibit the behavior of liquid crystals in the melt. The chains are so rigid that the interchain entanglement is minimal, and thus melts have a low viscosity. On cooling, the rods easily orient and produce a self-reinforcing polymer structure.

Predominant LCP components are p-benzene rings. For liquid crystal polyesters, the basic structural units are derived from materials such as p-hydroxybenzoic acid, terephthalic acid, and hydroquinone. To process the polymer more easily, some methods are used to adjust the chain chemistry. Vectra (Celanese) is reported to be based on p-hydroxybenzoic acid and hydroxynaphthoic acid monomers. Xydar is based on terephthalic acid, p-hydroxybenzoic acid, and pp'-dihydroxybiphenyl.

LCPs have high continuous use and heat distortion temperatures, low-smoke emission, low coefficient of thermal expansion, low water absorption, and excellent mechanical and impact properties.

LCPs are noted to have limiting oxygen index values in the 35 to 50 range. They generally suffer poor abrasion resistance.

Specific gravities of the test materials are given in the following table.

Test Materials' Specific Gravities

MATERIAL	SPECIFIC GRAVITY
Vectra A950	1.39
DuPont HX400	1.31
Xydar RC210	1.57

TENSILE TESTING OF LIQUID CRYSTAL POLYMERS IN LIQUID HYDROGEN

T. J. Eisenreich
General Dynamics Space Systems Division

General Dynamics Space Systems Division (GDSS) received fifteen (15) Liquid Crystal Polymer molded tensile specimens from Phillips Laboratory for liquid hydrogen testing.

The specimens were instrumented by GDSS with SK-13-125BB-350 axial strain gages bonded back-to-back with M-Bond 600 adhesive cured for two hours at 200°F. All tensile specimens except the DuPont HX 4000 coupons were tabbed with 2024-T3 aluminum alloy doublers bonded using EA 9330 paste adhesive cured for two hours at 180°F. The DuPont HX 4000 tensile specimens were tested in the as-received condition.

The specimens were tested on the 20, 000 lb capacity MTS servo-hydraulic test machine at a cross-heat travel rate of 0.05 inch per minute. The specimens were completely immersed in liquid hydrogen during loading. Load and strain data were recorded at one second intervals on an Orion/Macintosh Data Acquisition System to failure.

Table 1 lists the individual specimen test results generated on this program. Figure 1 is a schematic of the molded Liquid Crystal Polymer tensile specimen used in this program. This drawing also indicates the regions in which failure occurred as reported in Table 1. Figure 2 compares the average liquid hydrogen tensile strength and modulus generated of the various Liquid Crystal Polymers. There was a large scatter in the tensile strengths generated in liquid hydrogen. This scatter may be due in part to the method of processing (molding) of the tensile specimens. Modulii values showed less scatter than the tensile strengths with all values determined between 1000 and 3000 microstrain. Failure strain was determined by dividing the tensile strength by modulus.

The ultimate tensile strength of the XY DAR SRT-500 longitudinal specimens were not obtained. The values recorded in Table 1 and the values plotted in Figure 2 were based on the maximum load that occurred. Specimen I1 and I2 were initially tested without doublers. I1 slipped at an approximate load of 850 lb. At approximately 1100 lb the outer layer of Specimen I2 "peeled" from the specimen. The decision was made to tab the specimens with Aluminum doublers. The maximum loads were obtained using doublers but failures occurred between the adhesive and the specimen.

The average tensile strength and modulus of the Vectra A950 system was 62% greater in the longitudinal direction than in the transverse direction. The modulus generated on the XY DAR SRT 500 material was 30% stiffer than its closest competitor RC-210 and 70% greater than Vectra A950 Longitudinal property. The average tensile strength of XY DAR is at a minimum 18% higher in liquid hydrogen than RC-210 and 45% greater than DuPont HX 4000.

Plotted in Figures 3 through 17 are the stress-strain curves generated for the various Liquid Crystal Polymer systems. Shown in Figures 3 and 4 are the stress-strain charts for the Vectra A950 transverse specimens F1 and F2. These curves show a divergence of the strain from gages located back-to-back. Examination of these specimens shows layered material which may be of different densities. Specimen F3 failed prematurely in a large void located across both layers. The failures of specimens F1 and F2 seem to have started in one of the layers as apposed to starting at an edge.

Figures 10, 11, and 12 are stress-strain curves of the Vectra A950 longitudinal tensile specimens. All three charts indicate a "knee" in the curve. The "knee" is more pronounced in specimens H1 and H2 than H4. The failed specimens do not shed any light as to the reason for this abrupt change in stiffness.

Table 1. Liquid Hydrogen Tensile Test Results on Liquid Crystal Polymers.

Material	Specimen I.D.	Width (in)	Thickness (in)	Ultimate Load (lb)	Ultimate Strength (ksi)	Modulus (msi)	Failure Strain (ue)	Failure Location
Vectra A950 Longitudinal	H1	0.5495	0.1231	1379	20.39	2.30	8864	III
	H2	0.5505	0.1232	1507	22.22	2.05	10839	I
	H4	0.5509	0.1285	1332	18.82	2.70	6969	I
	Avg	**0.5503**	**0.1249**	**1406**	**20.47**	**2.35**	**8891**	
	Std. Dev.	**0.0007**	**0.0031**	**91**	**1.70**	**0.33**	**1935**	
	COV	**0.13%**	**2.47%**	**6.44%**	**8.32%**	**13.95%**	**21.77%**	
Vectra A950 Transverse	F1	0.5631	0.1210	553	8.12	0.85	9549	III
	F2	0.5690	0.1206	653	9.52	0.95	10017	III
	F3	0.5790	0.1216	377	5.35	0.82	6530	III
	Avg	**0.5704**	**0.1211**	**528**	**7.66**	**0.87**	**8698**	
	Std. Dev.	**0.0080**	**0.0005**	**140**	**2.12**	**0.07**	**1892**	
	COV	**1.41%**	**0.42%**	**26.48%**	**27.64%**	**7.79%**	**21.76%**	
DuPont HX 4000 Longitudinal	G2	0.5631	0.1200	839	12.42	2.73	4548	III
	G3	0.5690	0.1191	952	14.05	3.23	4349	III
	G4	0.5476	0.1193	1103	16.88	3.55	4756	I
	Avg	**0.5599**	**0.1195**	**965**	**14.45**	**3.17**	**4551**	
	Std. Dev.	**0.0111**	**0.0005**	**132**	**2.26**	**0.41**	**203**	
	COV	**1.97%**	**0.40%**	**13.73%**	**15.65%**	**13.04%**	**4.47%**	

Table 1. Liquid Hydrogen Tensile Test Results on Liquid Crystal Polymers.

Material	Specimen I.D.	Width (in)	Thickness (in)	Ultimate Load (lb)	Ultimate Strength (ksi)	Modulus (msi)	Failure Strain (ue)	Failure Location
XY DAR SRT-500 Longitudinal	I1	0.5494	0.1201	1798	27.25	8.11	3360	*
	I2	0.5487	0.1185	1894	29.13	8.25	3531	*
	I3	0.5493	0.1191	1490	22.78	8.48	2686	*
	Avg	**0.5491**	**0.1192**	**1727**	**26.38**	**8.28**	**3192**	
	Std. Dev.	**0.0004**	**0.0008**	**211**	**3.26**	**0.19**	**447**	
	COV	**0.07%**	**0.68%**	**12.22%**	**12.37%**	**2.26%**	**14.00%**	
RC-210 Longitudinal	J3	0.5533	0.1241	1239	18.04	5.42	3329	III
	J4	0.5512	0.1234	1665	24.48	5.98	4093	II
	J6	0.5514	0.1234	1547	22.74	5.95	3821	III
	Avg	**0.5520**	**0.1236**	**1484**	**21.75**	**5.78**	**3748**	
	Std. Dev.	**0.0012**	**0.0004**	**220**	**3.33**	**0.32**	**387**	
	COV	**0.21%**	**0.33%**	**14.82%**	**15.30%**	**5.45%**	**10.33%**	

* Specimen did not reach ultimate load. Failure occurred in bond between doubler and specimen.

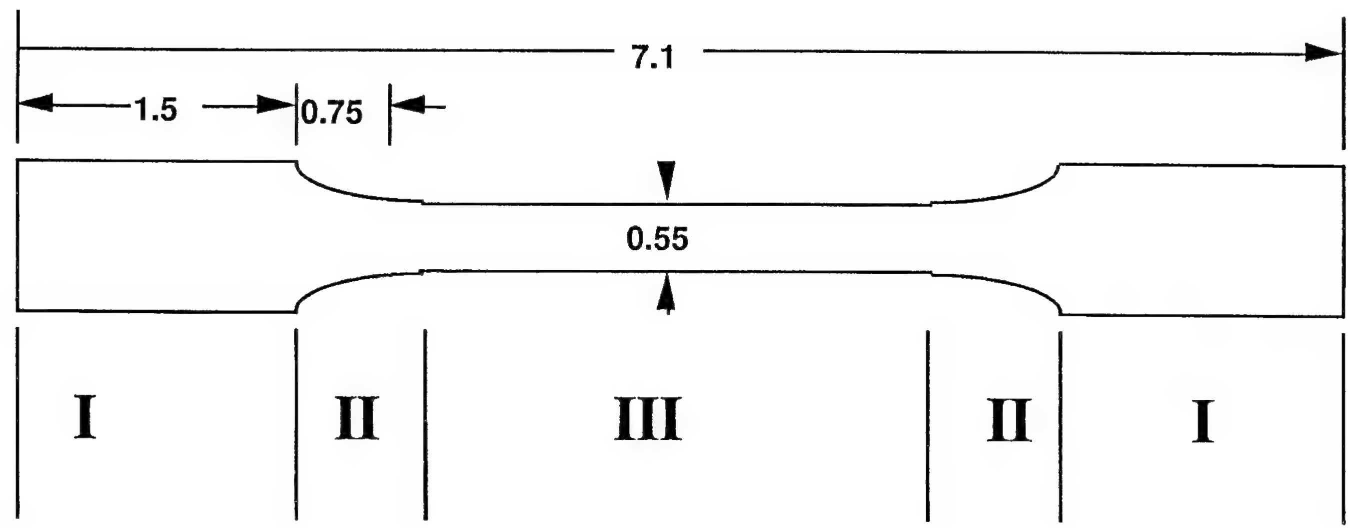


Figure 1. *Schematic of Molded Liquid Crystal Polymer Tensile Specimen Used to Generate Liquid Hydrogen Tensile Properties. Region I represents the area in which the aluminum doublers were bonded. Failure in this region usually occurred at the end of the doubler. Region II is defined from the start of the radius to the test section. Failures in this region usually occurred at the intersection of Region I and II. Region III is defined as the test section. Failures usually occurred at or near the center of the specimen.*

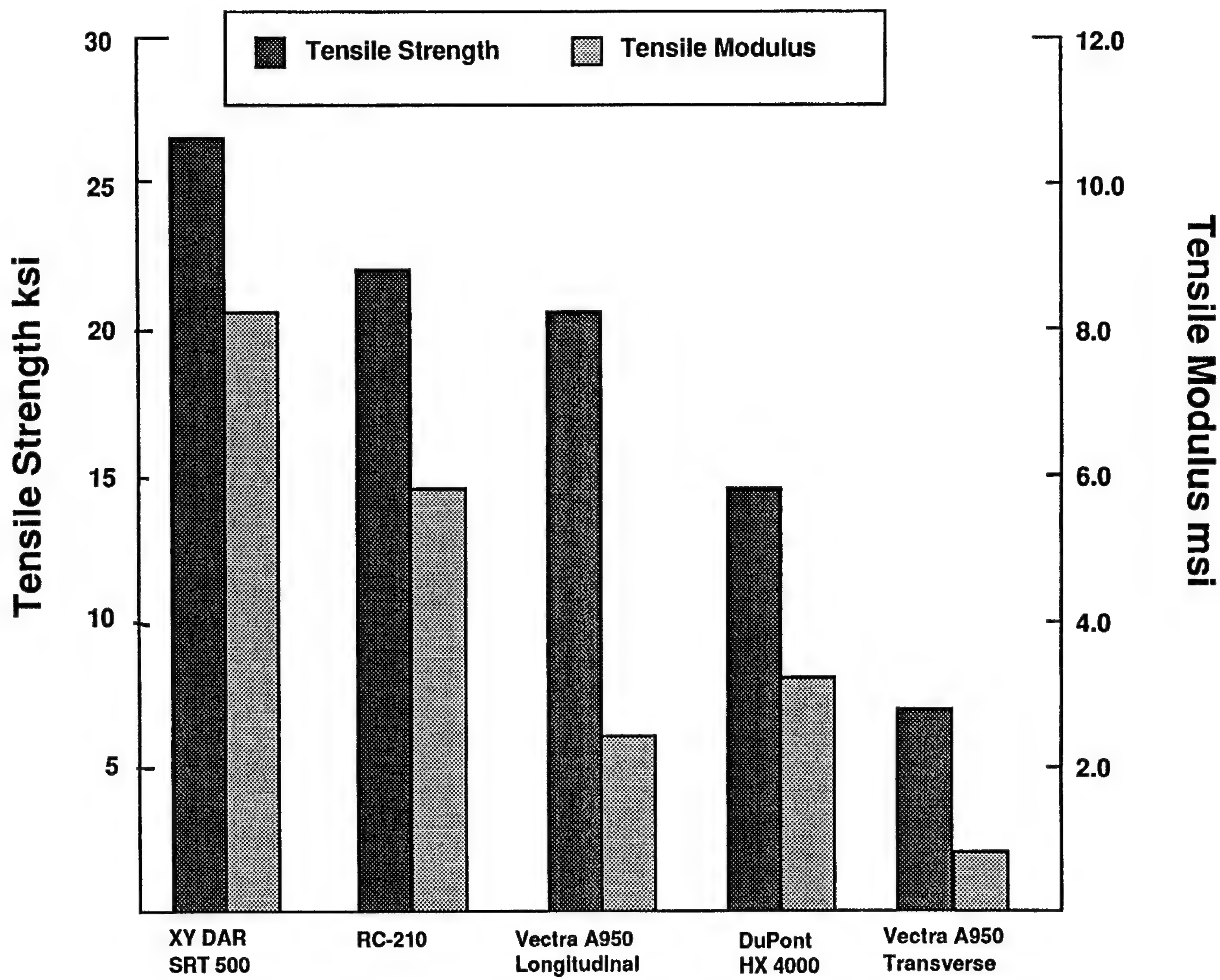


Figure 2. Comparison of the Tensile Strength and Modulus for the Various Liquid Crystal Polymers Generated in Liquid Hydrogen. Note that the Tensile Strength for XY DAR SRT 500 Shown ***Is Not*** *Ultimate Strength But Maximum Stress Obtained.*

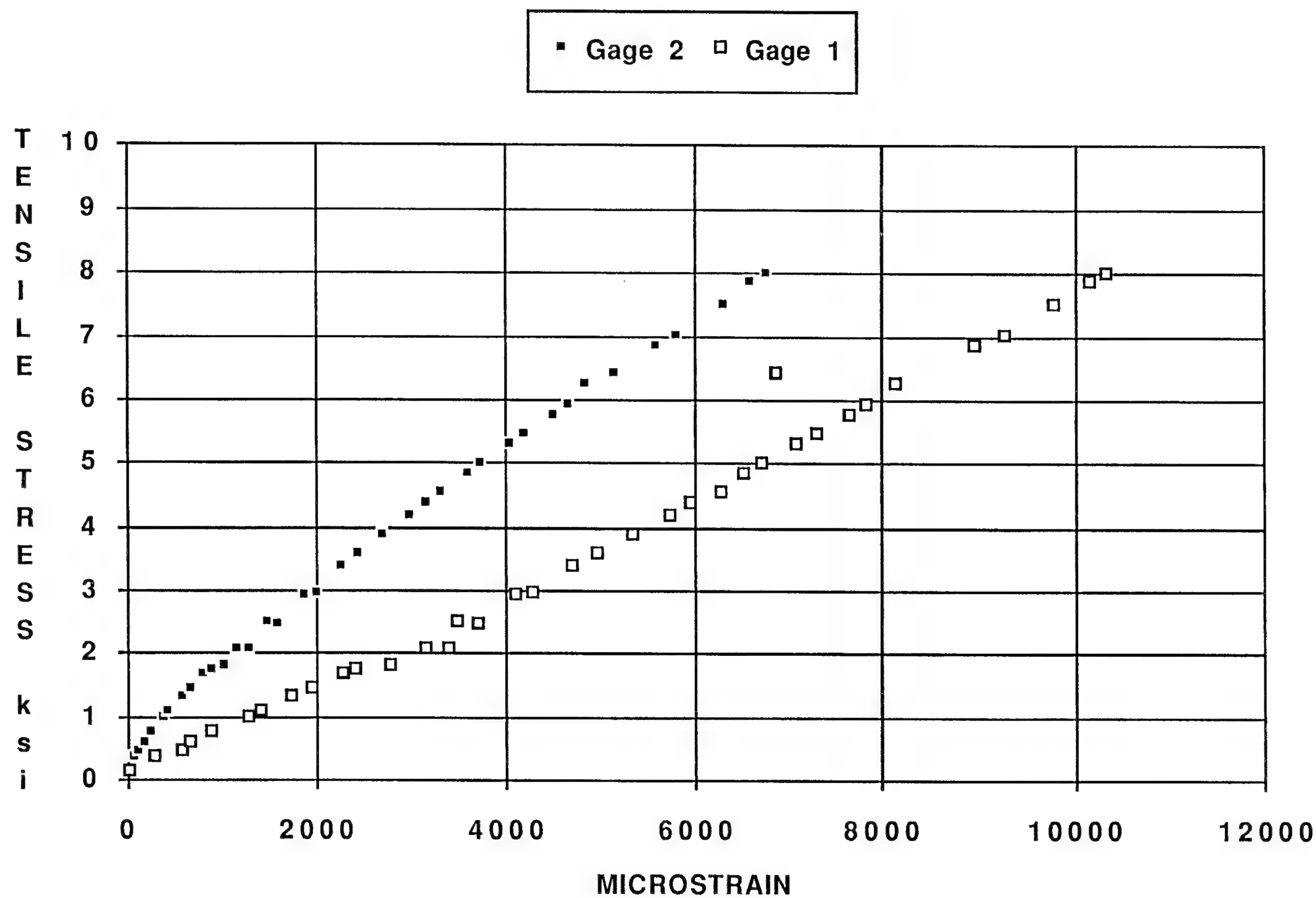


Figure 3. Vectra A950 Transverse Specimen F1 Stress - Strain Curve Generated in Liquid Hydrogen.

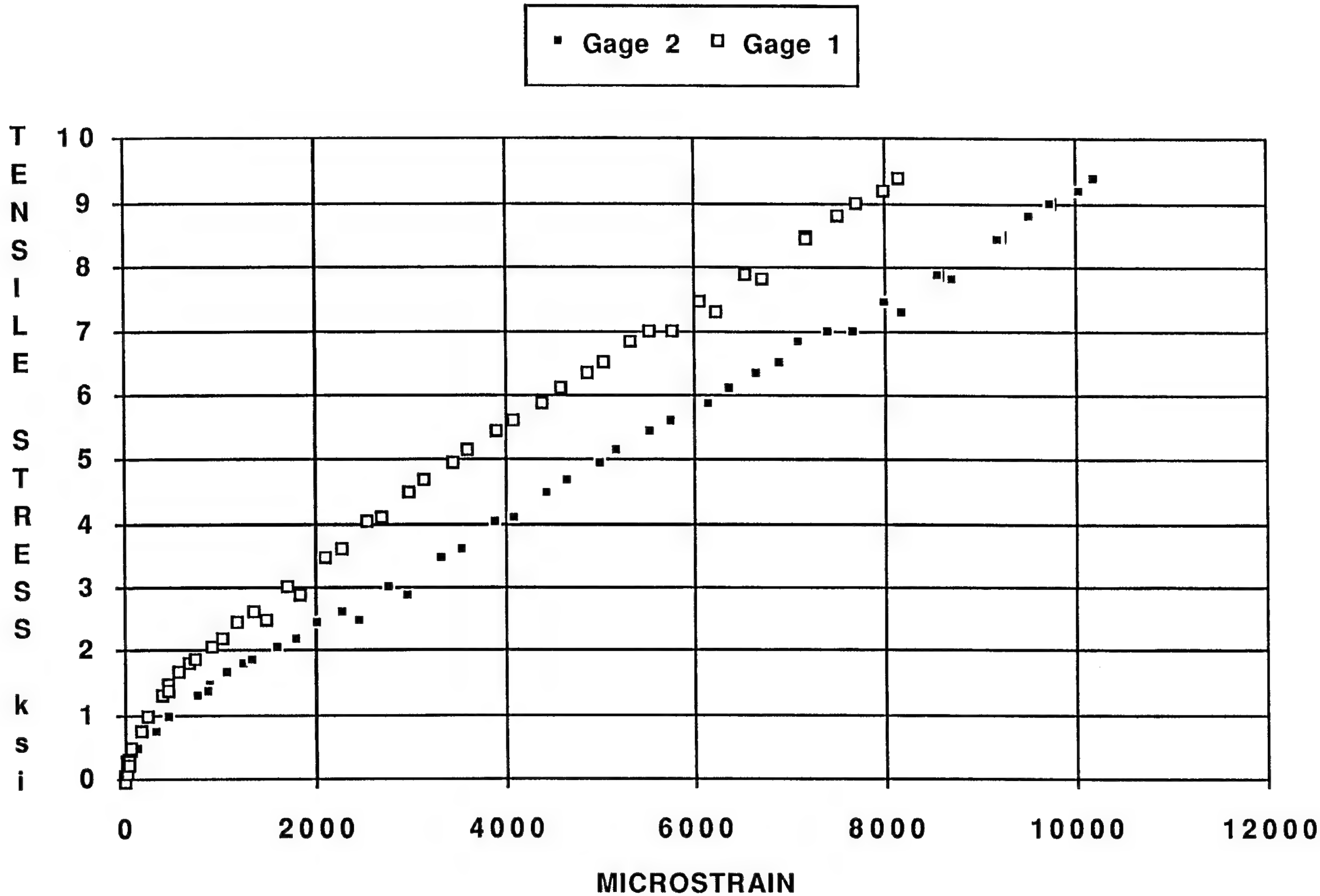


Figure 4. Vectra A950 Transverse Specimen F2 Stress - Strain Curve Generated in Liquid Hydrogen.

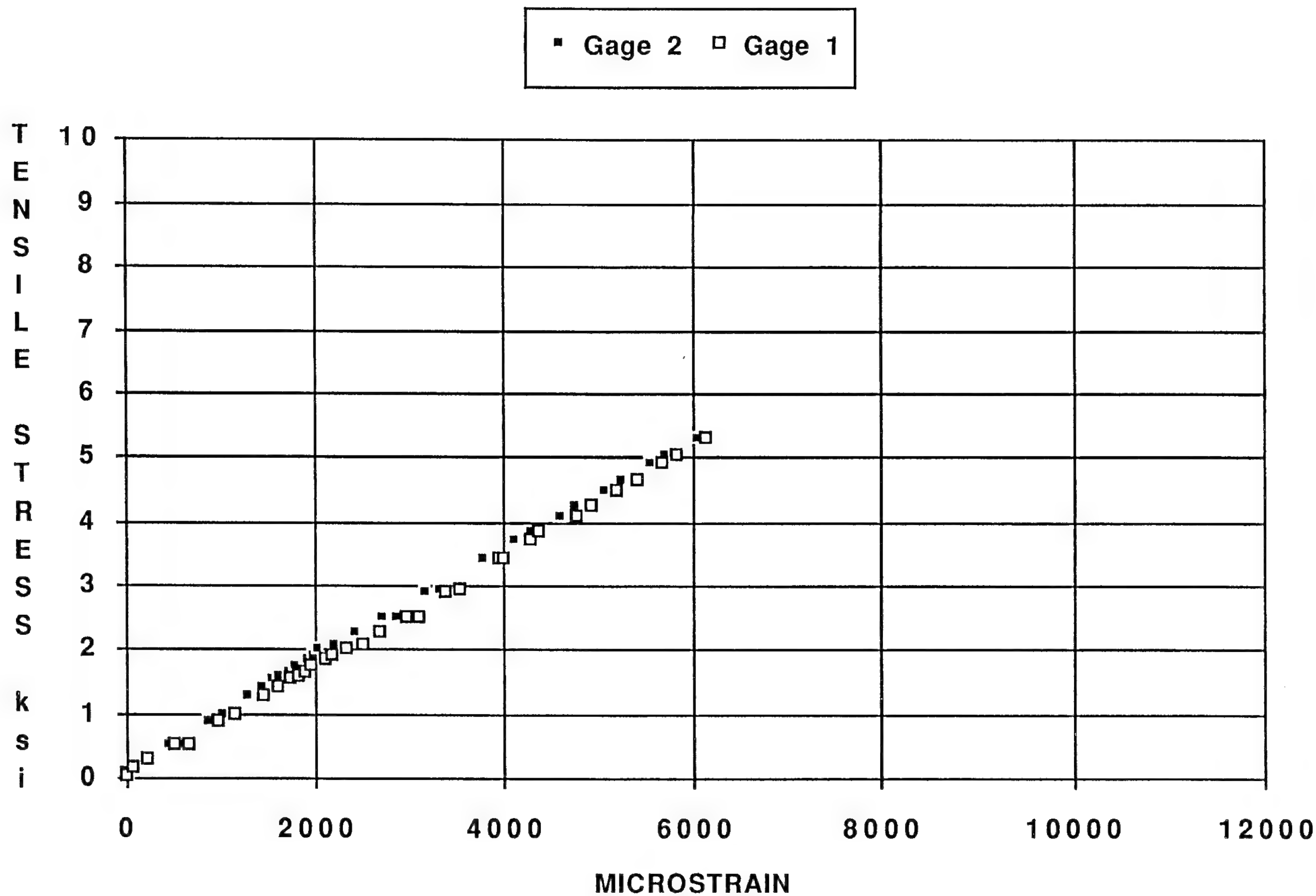


Figure 5. Vectra A950 Transverse Specimen F3 Stress - Strain Curve Generated in Liquid Hydrogen.

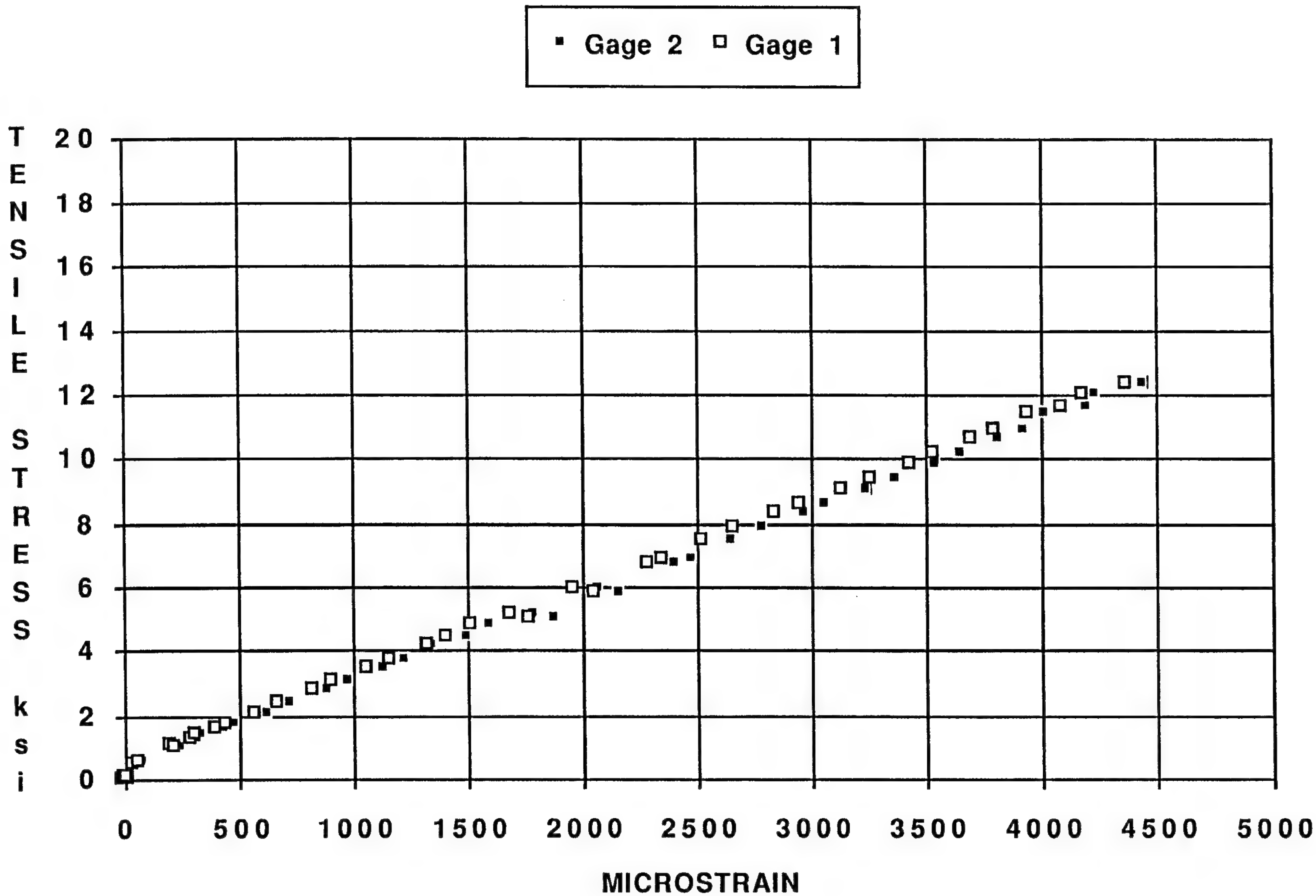


Figure 6. DuPont HX 4000 Longitudinal Specimen G1 Stress - Strain Curve Generated in Liquid Hydrogen.

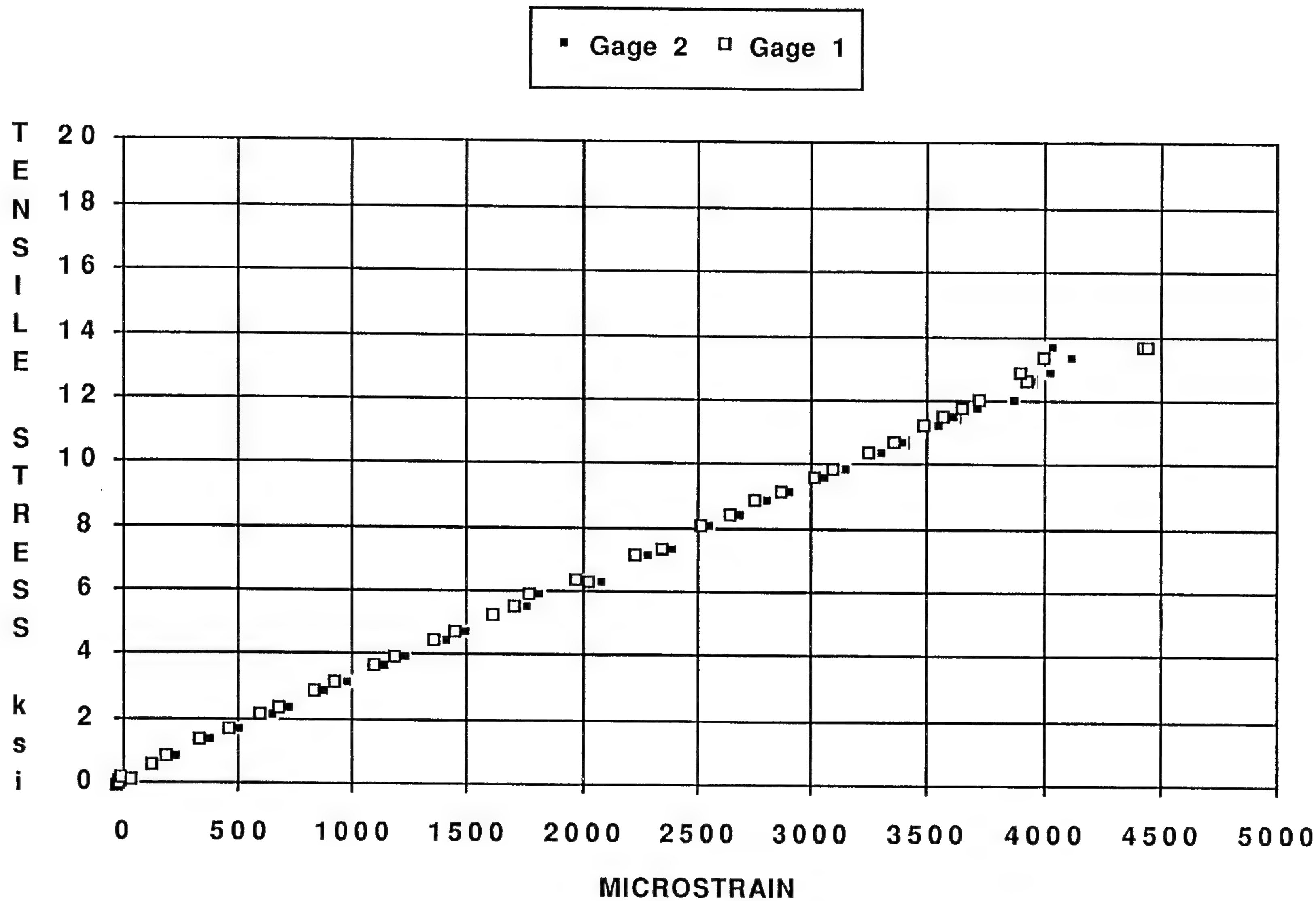


Figure 7. DuPont HX 4000 Longitudinal Specimen G3 Stress - Strain Curve Generated in Liquid Hydrogen.

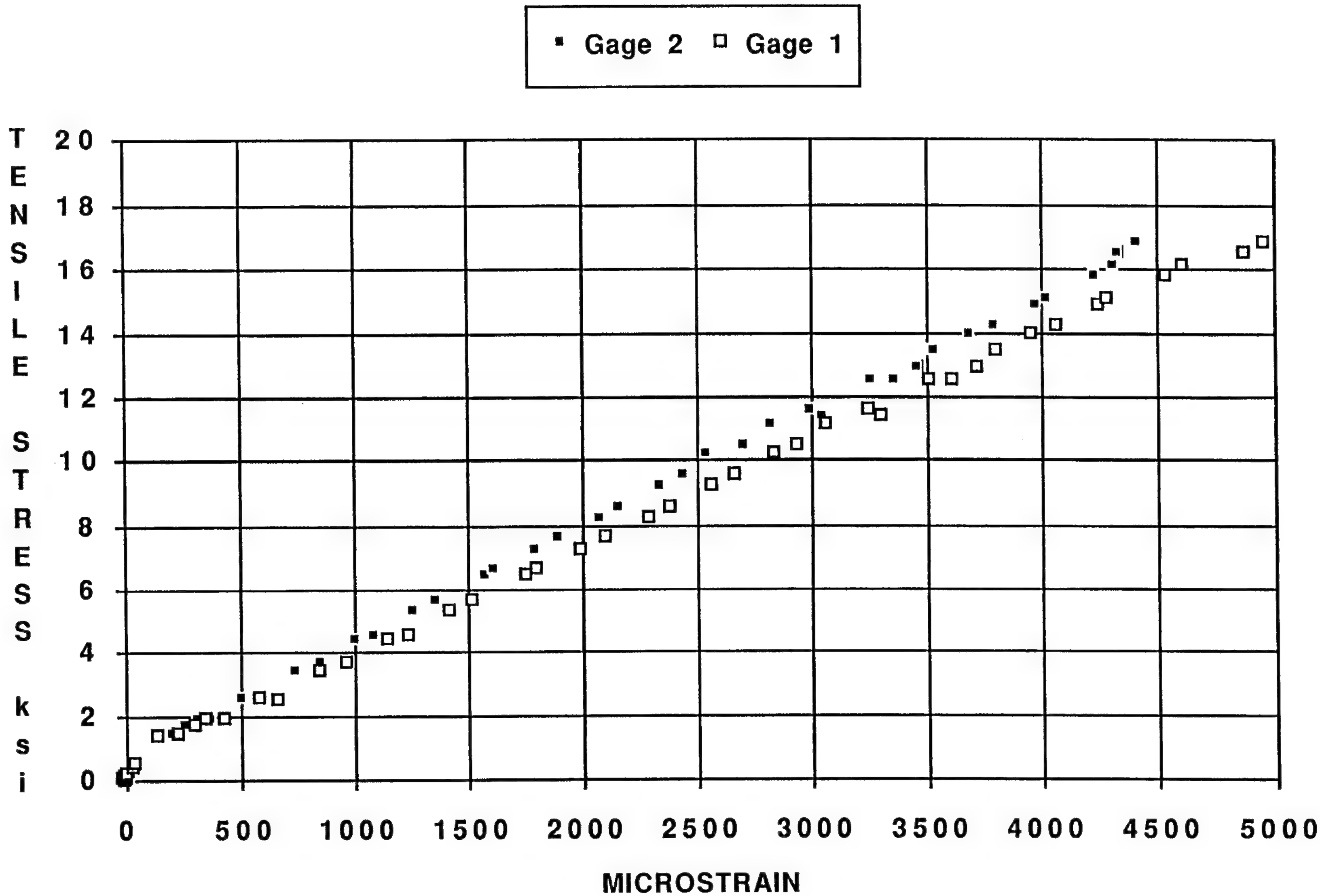


Figure 8. DuPont HX 4000 Longitudinal Specimen G4 Stress - Strain Curve Generated in Liquid Hydrogen.

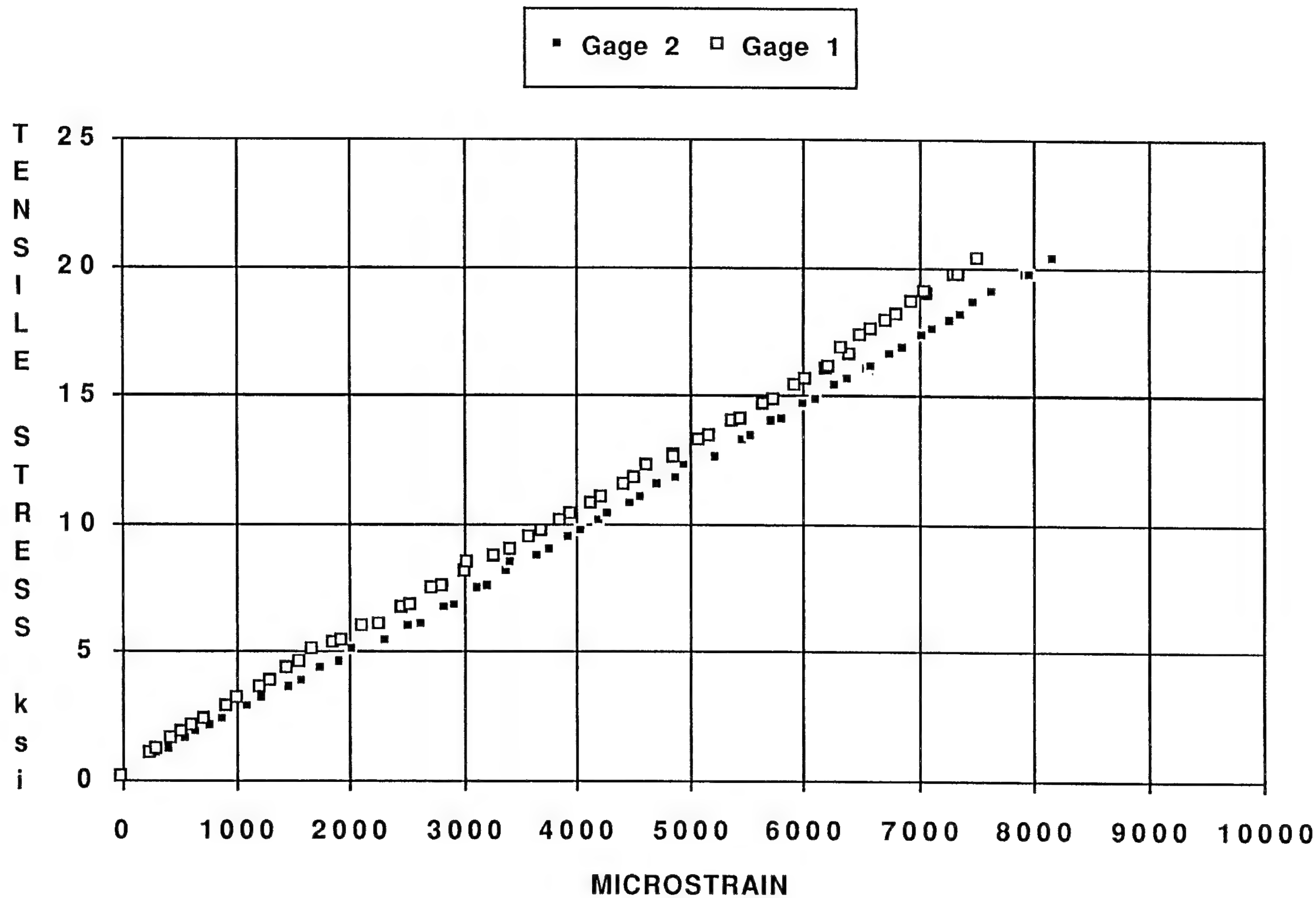


Figure 9. Vectra A950 Longitudinal Specimen H1 Stress - Strain Curve Generated in Liquid Hydrogen.

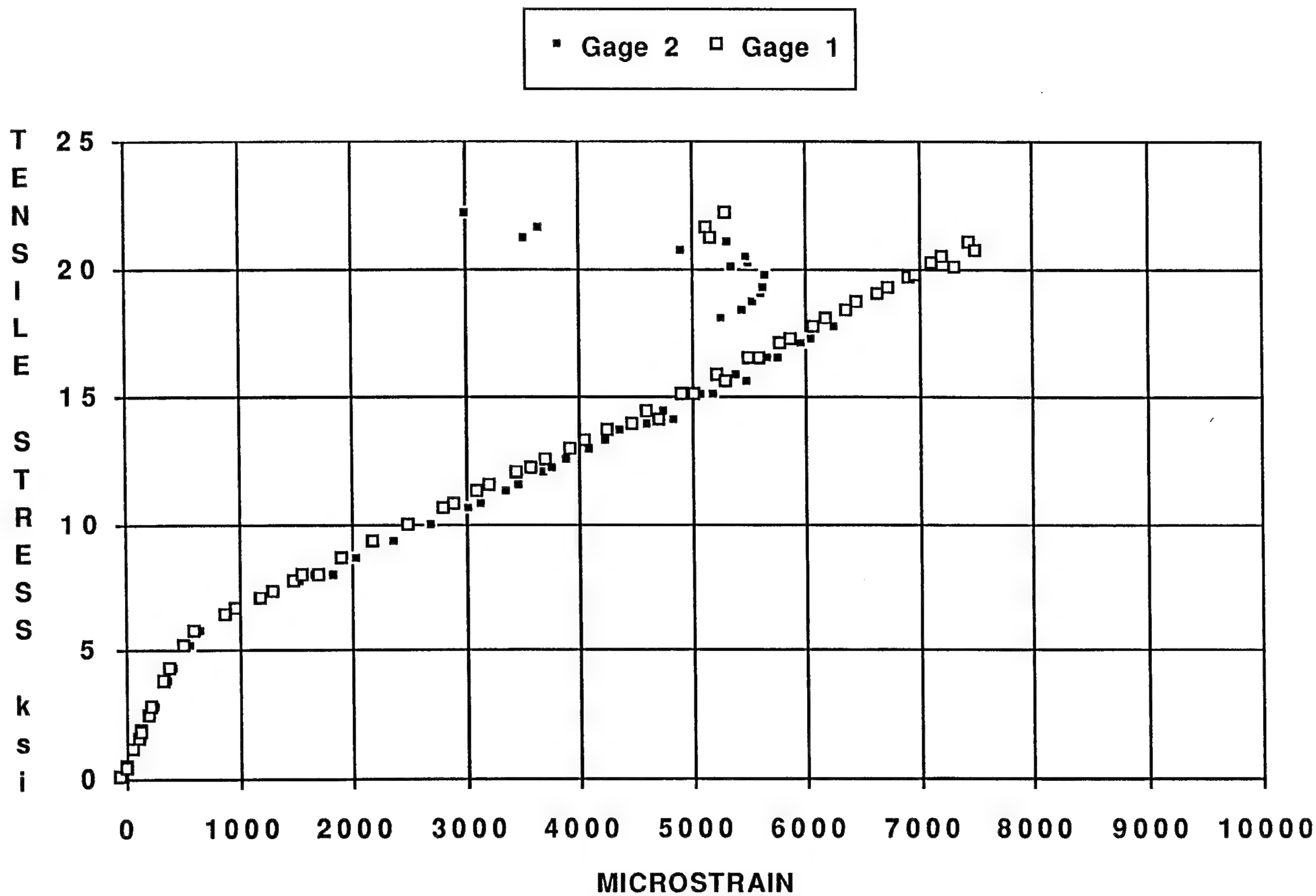


Figure 10. Vectra A950 Longitudinal Specimen H2 Stress - Strain Curve Generated in Liquid Hydrogen.

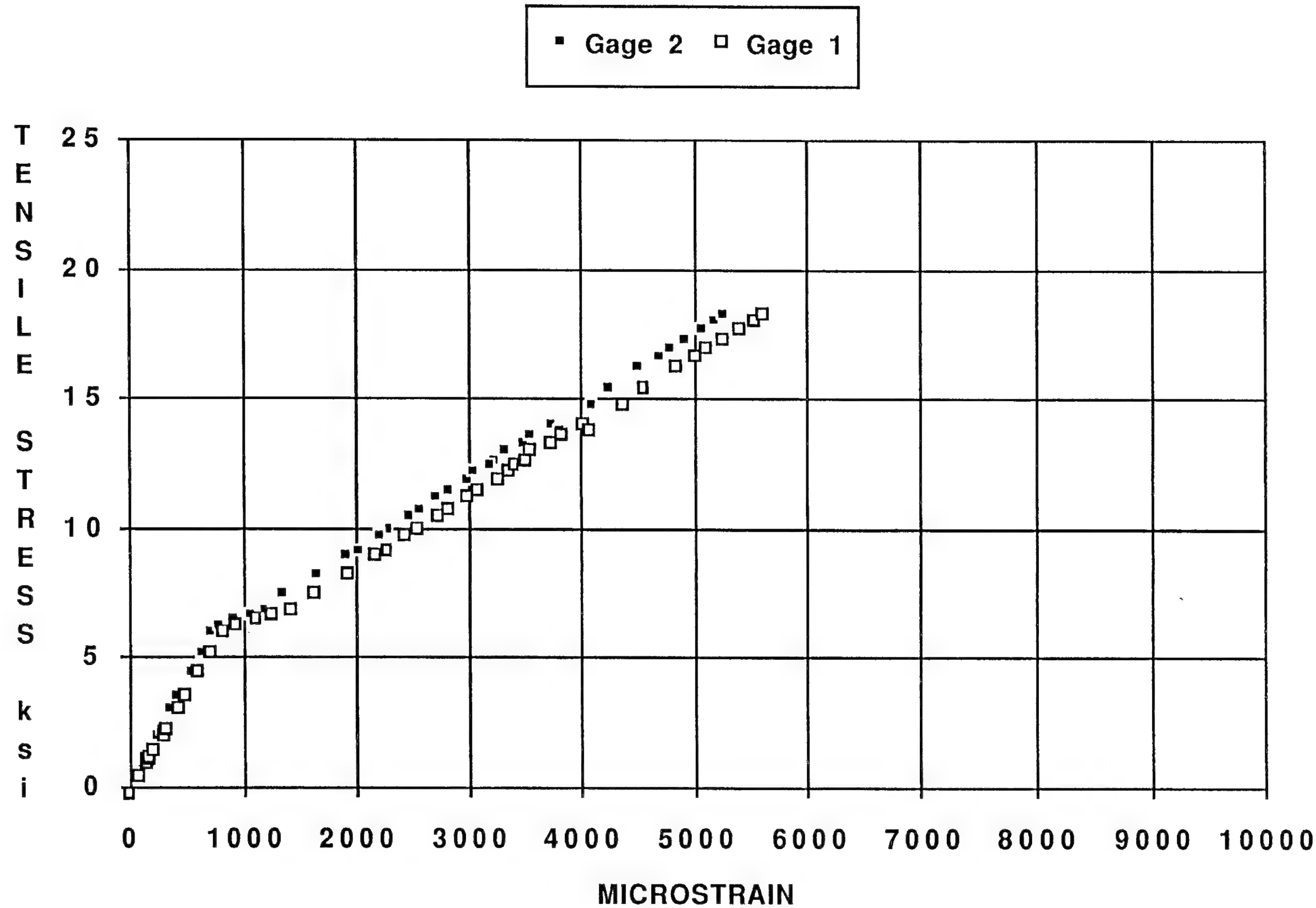


Figure 11. Vectra A950 Longitudinal Specimen H4 Stress - Strain Curve Generated in Liquid Hydrogen.

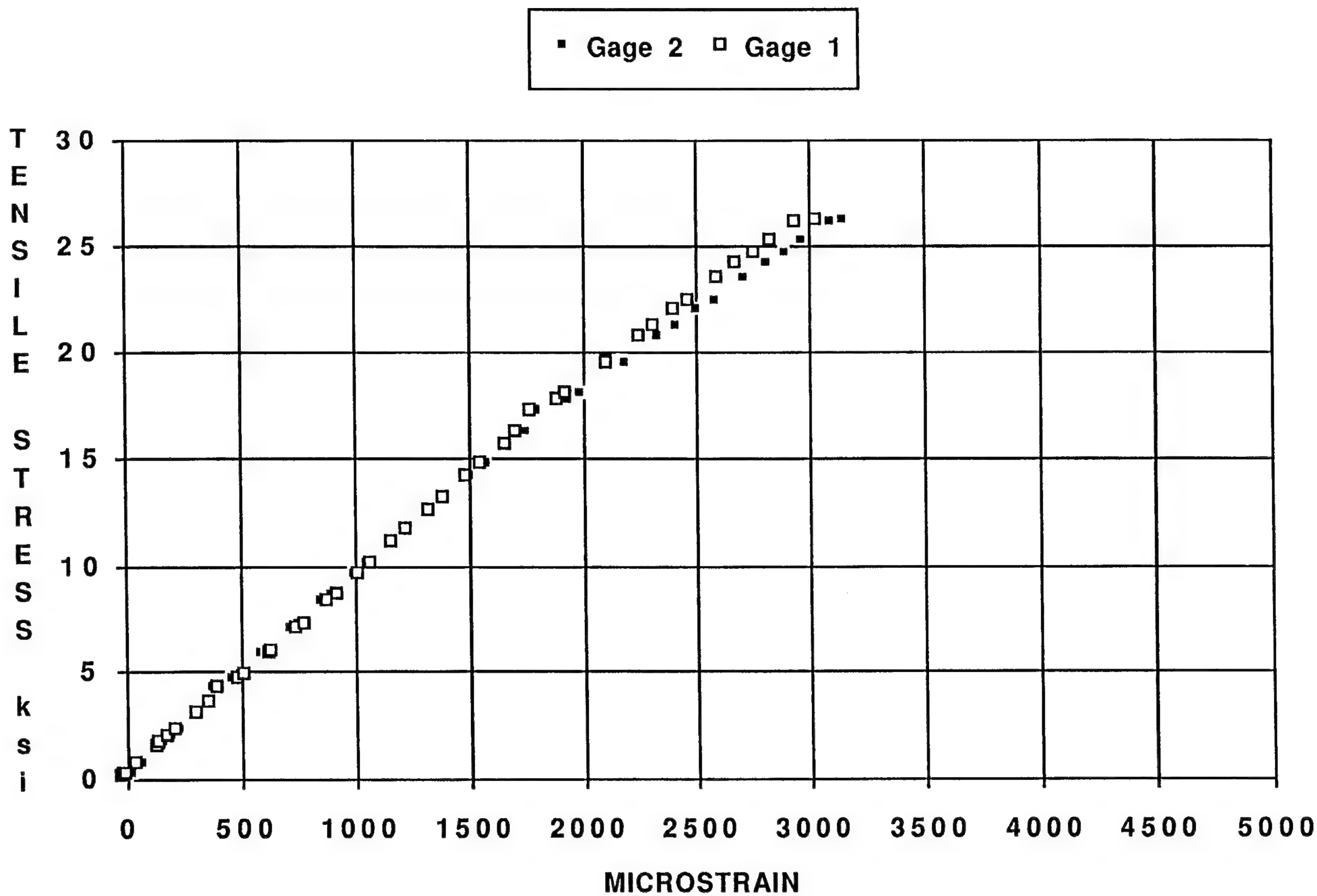


Figure 12. XYDAR SRT 500 Longitudinal Specimen I1 Stress - Strain Curve Generated in Liquid Hydrogen. The specimen did not fail at the ultimate stress level shown on this chart.

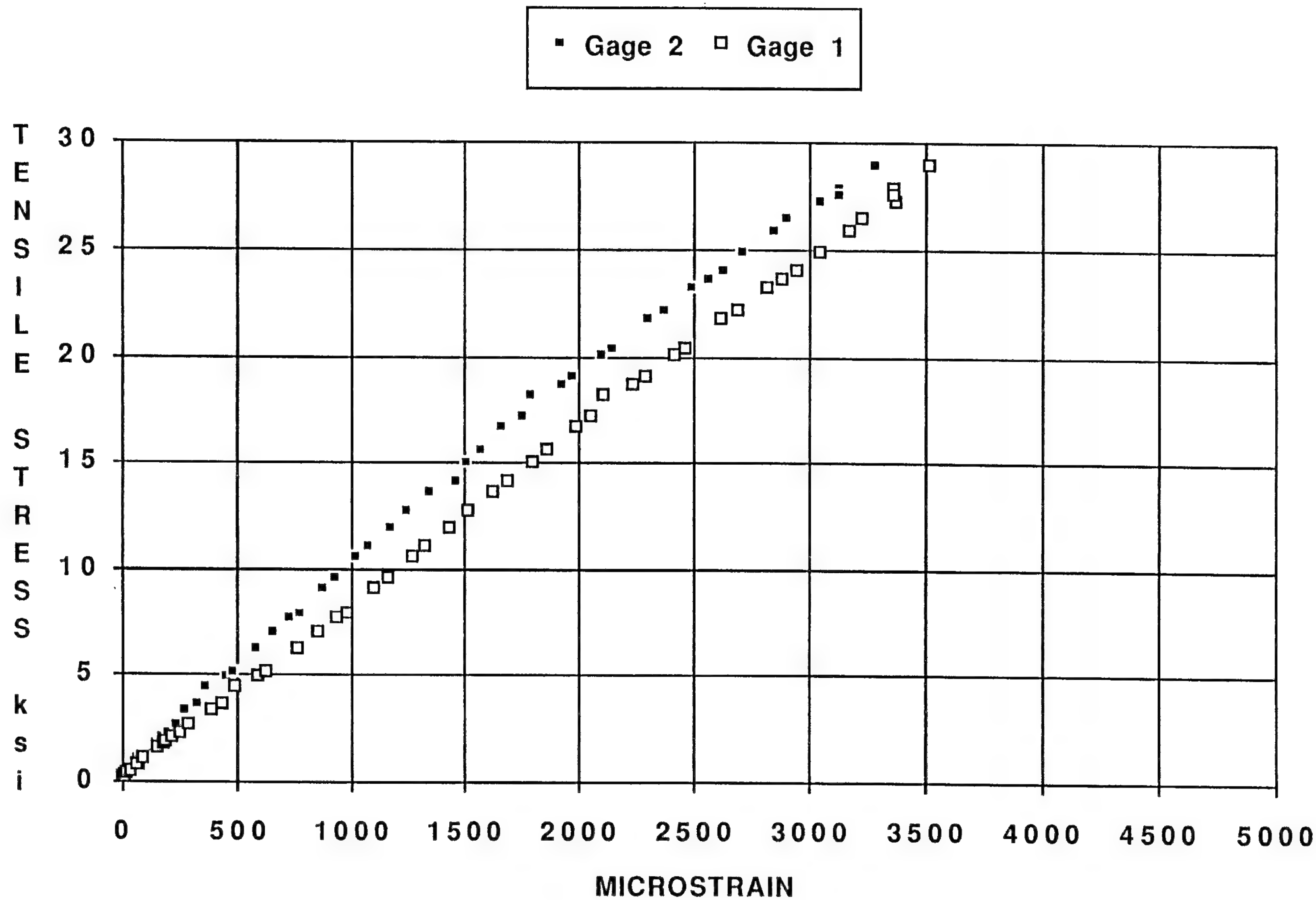


Figure 13. XYDAR SRT 500 Longitudinal Specimen I2 Stress - Strain Curve Generated in Liquid Hydrogen. The specimen did not fail at the ultimate stress level shown on this chart.

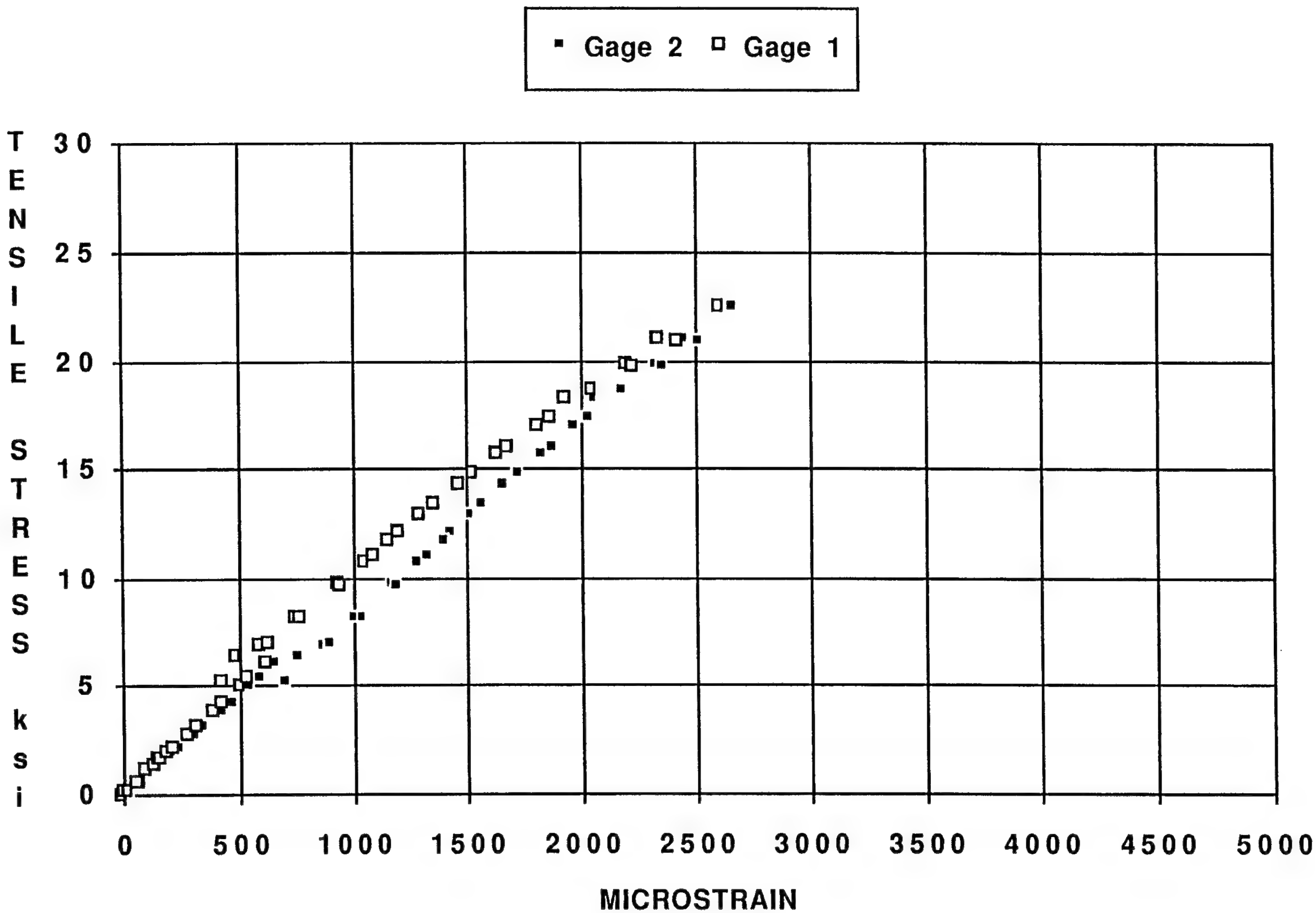


Figure 14. *XYDAR SRT 500 Longitudinal Specimen I3 Stress - Strain Curve Generated in Liquid Hydrogen. The specimen did not fail at the ultimate stress level shown on this chart.*

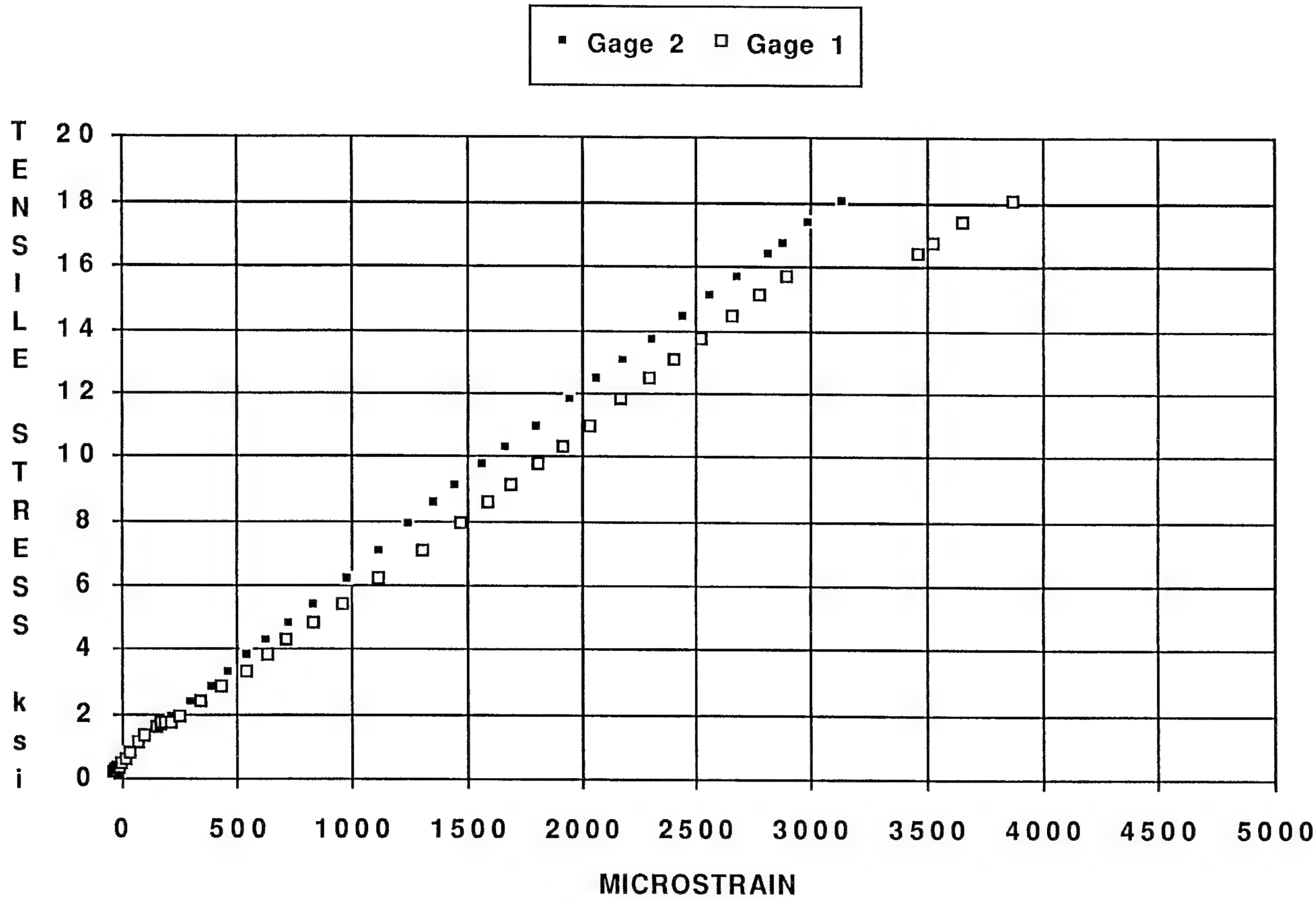


Figure 15. RC 210 Longitudinal Specimen J3 Stress - Strain Curve Generated in Liquid Hydrogen.

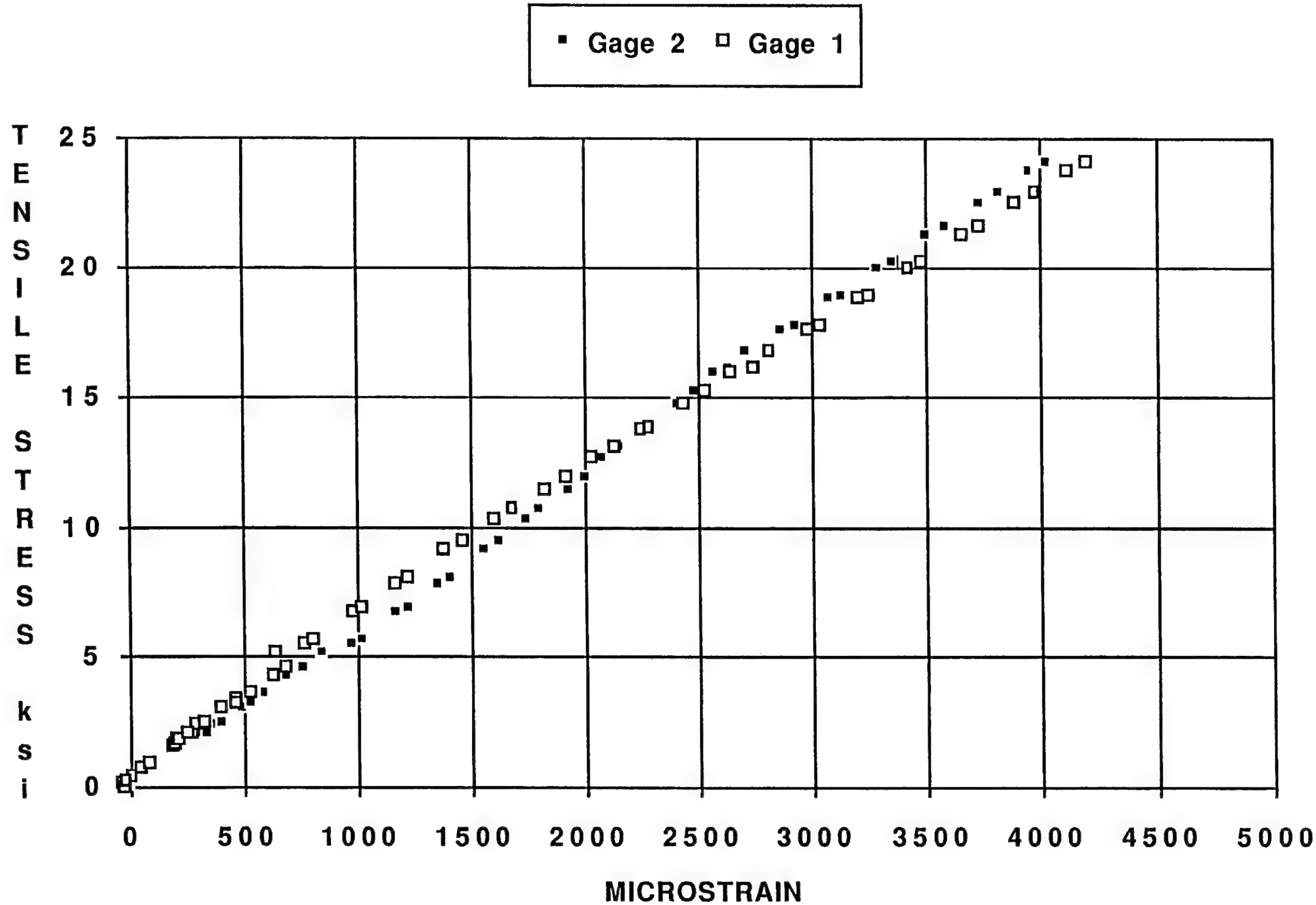


Figure 16. RC 210 Longitudinal Specimen J4 Stress - Strain Curve Generated in Liquid Hydrogen.

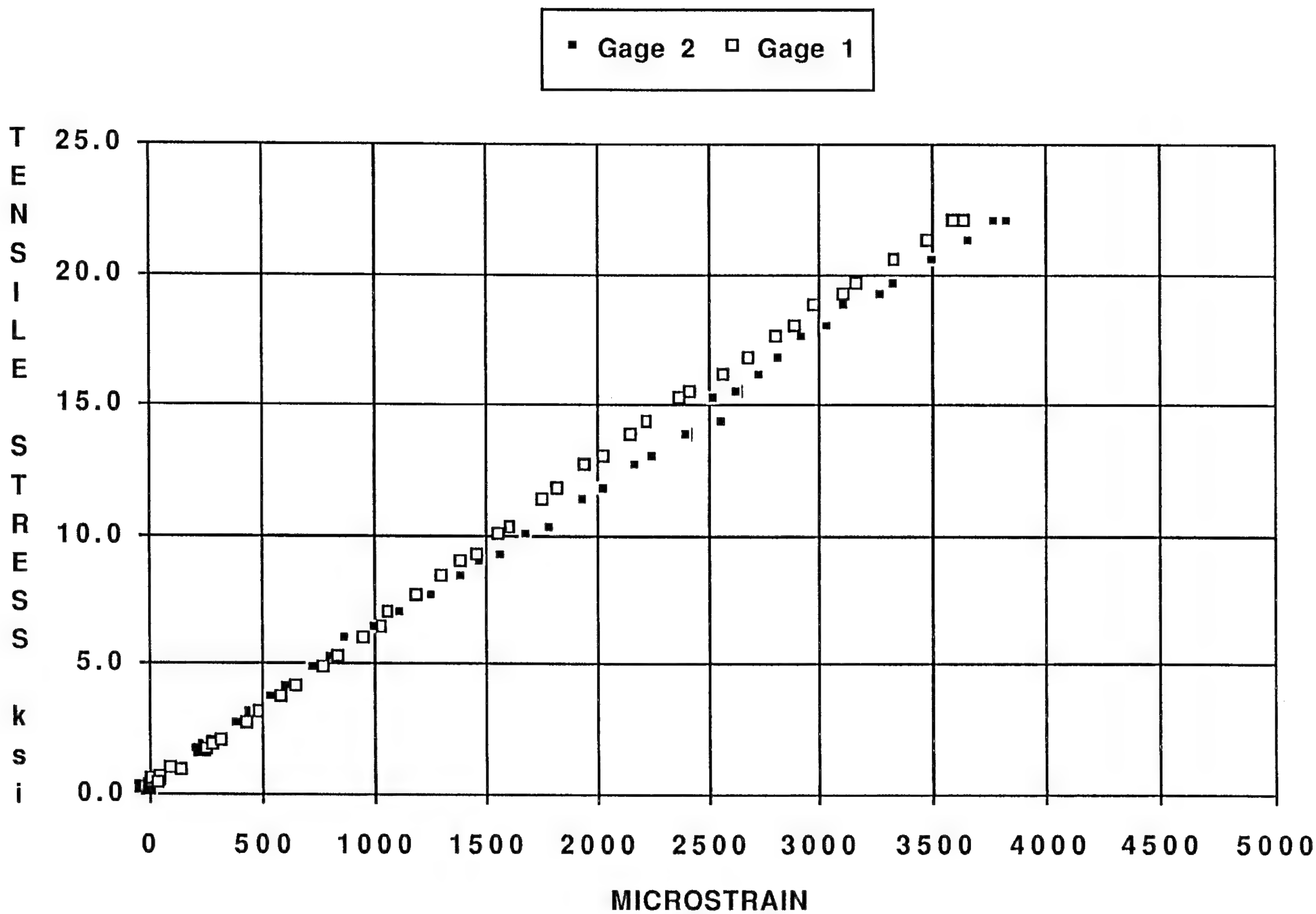


Figure 17. RC 210 Longitudinal Specimen J6 Stress - Strain Curve Generated in Liquid Hydrogen.

UES AFOSR Final Report

TENSILE TESTING OF LIQUID CRYSTAL POLYMERS

Tracy Reed
United States Air Force
26 August, 1990

I would like to thank Dr. John Rusek and Dr. Shannon Lieb for all their help during my time at the Astonautics Lab.

During my eight weeks working at the Astronautics Laboratory I worked on two projects, Methods for Analysis of Reactive Surfaces (MARS) and Advanced Polymer Components (APC). For the MARS program my project was to grow ammonium perchlorate (AP) crystals, and for APC I was to do tensile testing on several advanced polymers. I also used the ISP program to compute the theoretical ISP's of rocket propellants we came up with.

I began my summer by checking out several books from the Technical Library at the Astronautics Laboratory. I learned all I could about crystal structure, growth, and methods of growing AP crystals from these books. I then choose the method I thought to be the most suitable.

The last time AP crystals of any considerable size had been grown was at China Lake Naval Weapons Center in the early seventies. The scientists there choose the temperature control method to grow the crystals. They lowered the temperature by one tenth of a degree per day causing the water that the AP was dissolved in to hold less AP. The extra AP that the water could not hold grew on the seed crystals suspended in the solution. Lowering the temperature at this rate was not suitable for our purposes. I choose the evaporation method the be most the

most appropriate. I built a device to grow the crystals in which consisted of a large glass container with a seed crystal mounted in it. The seed crystal was glued to a length of bent glass that held the crystal securely in the center of the solution. The container had a lid on it with several holes in it to let the water evaporate. The evaporation of the water slowly raises the concentration of the AP until the water can no longer hold it all and the excess begins forming on the seed crystal thereby increasing its size.

The container holds two liters of water to which I added about four hundred grams of AP. As it dissolved in the water a foam began to collect on the top. I eventually concluded that this was an additive in the AP, an anti-caking agent. I spent several days filtering out the additive.

I then set up the experiment one morning but by that afternoon the seed crystal had dissolved. The next morning hundreds of tiny crystals had grown in the bottom of the container. This proved to us that the temperature in the laboratory was not stable enough to grow crystals in. I decided the whole experiment needed to be put in a temperature bath. The temperature controller for this bath has been ordered and as soon as it gets in the crystal growth experiment will continue.

I also worked on the APC project. The goal was to put the specimens through tensile testing under various conditions

and compare it to the published data to see which method gave us the most accurate data. The specimens are to be tested on the 50,000 pound MTS machine at the Composites Lab. The specimens to be tested are Ryton, Vectra C130, and Vectra A625. A test matrix was created that included all the conditions we wanted to test the specimens under, such as dogboned or rectangular. I cut the proper number of dogbones from each material as specified by the test matrix. Then I sanded the ones that required sanding. The specimens were cleaned, load tabs glued on, and strain gauges put in place. Then the leads were soldered to the strain gauges. The actual testing of the materials began shortly after I left.

I also worked on many different types of computers and became familiar with many operating systems while I was at the Astronautics Lab. On the PC I used the ISP computer program to do theoretical calculations on many new rocket fuels being thought up by my colleagues. I learned how to input the data, analyze the output, and compare these against the standard Hydrogen and Oxygen fuel mixture.

I also used the Vax facility at the AL and the Cray 2 at Kirtland AFB to assist in using MOPAC and CADPAC. We used these programs to come up with an accurate model of AP for MARS.

INJECTION MOLDED ROCKET MOTOR CASE

Christopher L. Frank
USAF Advanced Composites Program Office
January 1991

This paper will highlight the work being performed by the ACPO located at McClellan AFB and the AFAL at Edwards AFB . We will briefly touch on three main areas: the use of LCPs and their special appeal to this project; the 2X4 project; and finally the early results of work with the 2X4 prototypes.

BACKGROUND

In September 1989, an informational meeting was held at McClellan AFB to discuss the Advanced Polymer Composites (APC) project under the direction of the Astronautics Laboratory in February 1990. A co-operative effort began between the AFAL and the ACPO to rapidly build a number of rocket motor and rocket engine parts using a new type of plastic, Liquid Crystal Polymers or LCPs. This particular material had not been used in this type of application before. The AFAL wanted to quickly establish an Air Force-staffed plastic motor program and came to the ACPO for the expertise needed to design the molds and develop the processes to produce these motors. By May of 1990, the timetable was set, and design and analysis had begun. Molds were built, and on Aug 28, 1990, less than 6 months from concept, the first eleven plastic solid rocket motor cases were fired. Seven of these cases survived the firings. The initial success of this project has convinced the AFAL to continue working with the ACPO in this area. The use of plastic case designs for solid rocket motors will contribute greatly to the ultimate goal of a low-cost lightweight interceptor.

MATERIALS

LCPs have a number of intriguing properties that could prove very beneficial to the field of rocketry. The most significant of these are, high strength, resistance to extreme temperatures, and ease of molding highly detailed parts. We will discuss the origins of LCPs , the desirable properties of these polymers, and the LCPs used in this project.

Figure 1 shows a typical solid rocket motor schematic. The various mechanical parts constitute the majority of the total weight of the motor. If this total weight can be lowered, through the use of new engineering polymers like the LCPs, increased payloads or smaller rocket sizes may be realized. Beyond decreasing rocket motor weight the LCPs may also lower manufacturing costs, as various parts may be more efficiently manufactured by the use of injection or compression molding. For the purpose of this paper we will be primarily concerned with the motor case, though other components are currently under development.

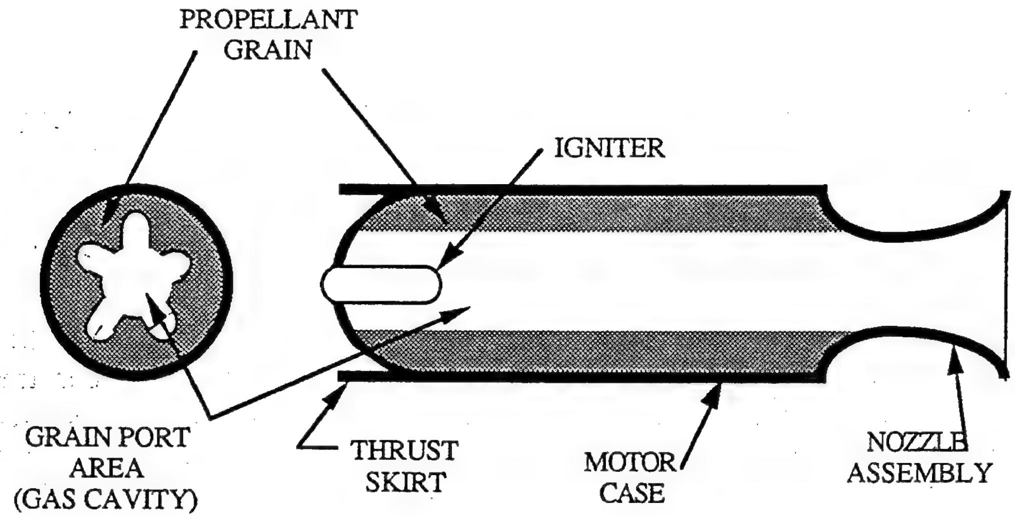


Fig. 1 Generic Solid Motor Design

The Carborundum company developed the early LCPs as aromatic thermosetting polyesters based on a para-oxybenzoic acid. The resulting materials, EKONOL* resin and EKKCEL* molding compounds, had the unique property of high crystallinity and so exhibited two times the modulus of polyimides. Although the melting temperature values were in the 900 ^{0} F-to-1000 ^{0} F range, they did decompose at elevated temperatures.

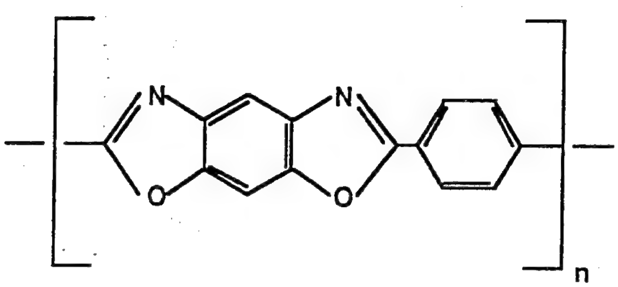


Fig. 2 LYOTROPIC POLYESTER

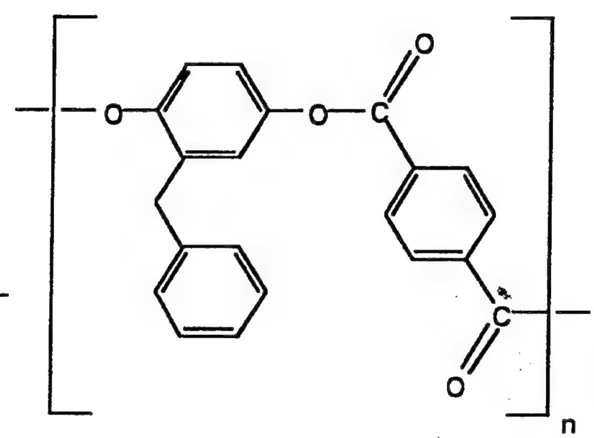


Fig. 3 THERMOTROPIC POLYESTERS

A new generation of these polymers are based on aromatic polyesters of p-hydroxybenzoic acid and hydroxynapthaic acid monomer. In 1965 DuPont introduced KEVLAR* aramid fiber. This material is lyotropic (Figure 2) or solution processible, meaning that various liquids are combined and

subsequently spun out as fibers (thermoset). In the 70's, Celanese developed a thermotropic or melt processible(thermoplastic) naphthalene-based material which was commercialized in the 80's as VECTRA*. (Figure 3) In the 80's, the Carborundum process was licensed to Dartco. Dartco developed a bisphenol-based resin line named XYDAR*. The trait common to all of these materials is their tendency to fiblirate or generate fibers on their own.

FIBER#	FIBER DIA.	AREA	LOAD	STRESS
1	0.015	1.767×10^{-4}	315 LBS.	1.78×10^{6} psi
2	0.012	1.131×10^{-4}	272 LBS.	2.41×10^{6} psi
3	0.008	0.5027×10^{-4}	403 LBS.	8.02×10^{6} psi
4	0.015	1.767×10^{-4}	443 LBS.	2.51×10^{6} psi
5	0.016	2.010×10^{-4}	415 LBS.	2.06×10^{6} psi
6	0.012	1.131×10^{-4}	442 LBS.	4.00×10^{6} psi
		AVERAGE	383 LBS.	3.46×10^{6} psi

FIBER TESTS
TABLE 1

Many of the current designs for rocket motors use fiber winding in one form or another to obtain the strengths required. A test was run on several fibers obtained during molding. These test results showed fiber strengths of 3,460,000 psi. for neat "A-series" VECTRA resin. (Table 1) Because of the fiber like behavior of these materials and the strength of those fibers, the scientists at the Astronautics Laboratory became interested in the use of these materials to develop new components for rocket applications. These component applications would exploit the natural fiberous tendencies of the LCPs, and could eventually be manufactured so that the fibers would form to re-enforce the structure as it is molded. This interest generated the APC 2X4 project that required the manufacture of a number of test articles.

The materials used in the preparations for the tests covered in this paper were Hoechst Celanese VECTRA A-625 a carbon flake filled or loaded LCP, VECTRA C-130 a glass filled or loaded LCP and a glass filled RYTON (PPS) or(polyphenylene-sulfide) a Phillips material compounded by Wilson-Fiberfil Inc.

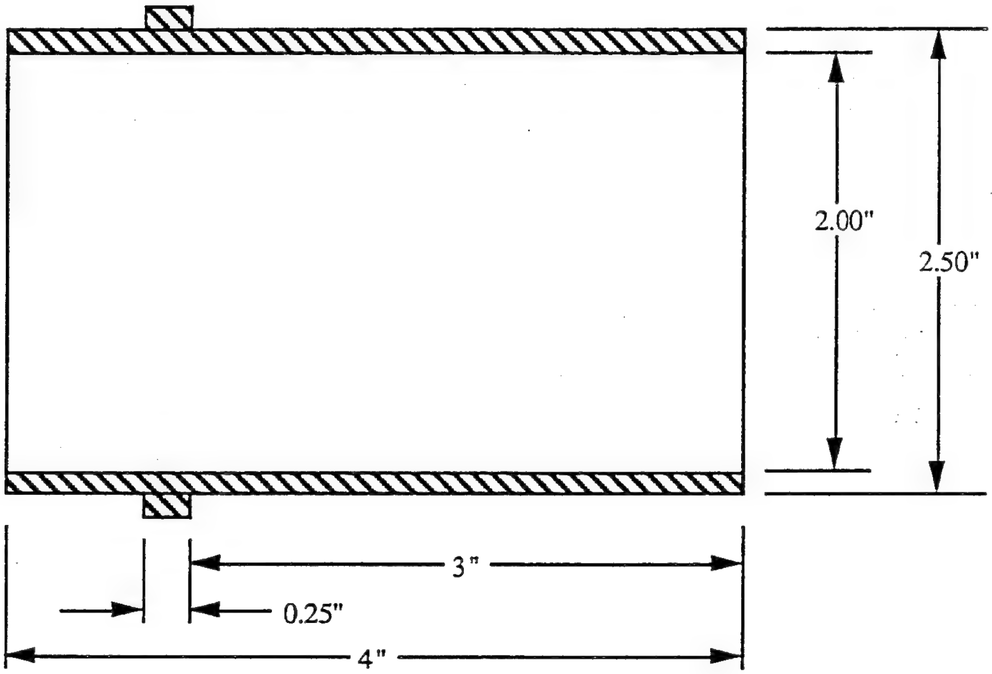


Fig. 4 2X4 TEST MOTOR CASE

The 2X4 motor for testing solid propellants was suggested as one of the first prototypes. Currently the 2X4 motor cases are made of D6AC steel and are individually machined. (Fig 4) The size of the case is 2" inside diameter and is 4" long, thus the name 2 by 4 motor. The manageable size of this case, the varied fuel types possible, and the fact that a test fixture and test program were already in place for the 2X4 made it an ideal candidate for this application.

The use of the 2X4 cases presented three primary design problems for mold construction; the production of a constant diameter cylinder, maintaining a uniform wall with no weld lines, and removal of the part after molding. The test fixtures for the 2X4 motors required that the case have a 2.50" outside diameter for the high pressure case (12000 psi) and 2.25" outside diameter for the low pressure case (2000 psi). This dimension must be held on each end to provide proper sealing during testing (see Fig. 5). The larger diameter fixture was chosen to allow both a thin and thick walled motor cases to molded and tested. Having chosen the larger case meant that the 2.50" outside diameter must be held over the length of the part. From past experience with flow analysis of cylindrical parts, it is known that the walls should fill from the top down or end-to-end to avoid weld lines. Plastics tend to shrink as they cool. This characteristic will cause the case to shrink tightly onto the core, so some means of removing the part must be provided.

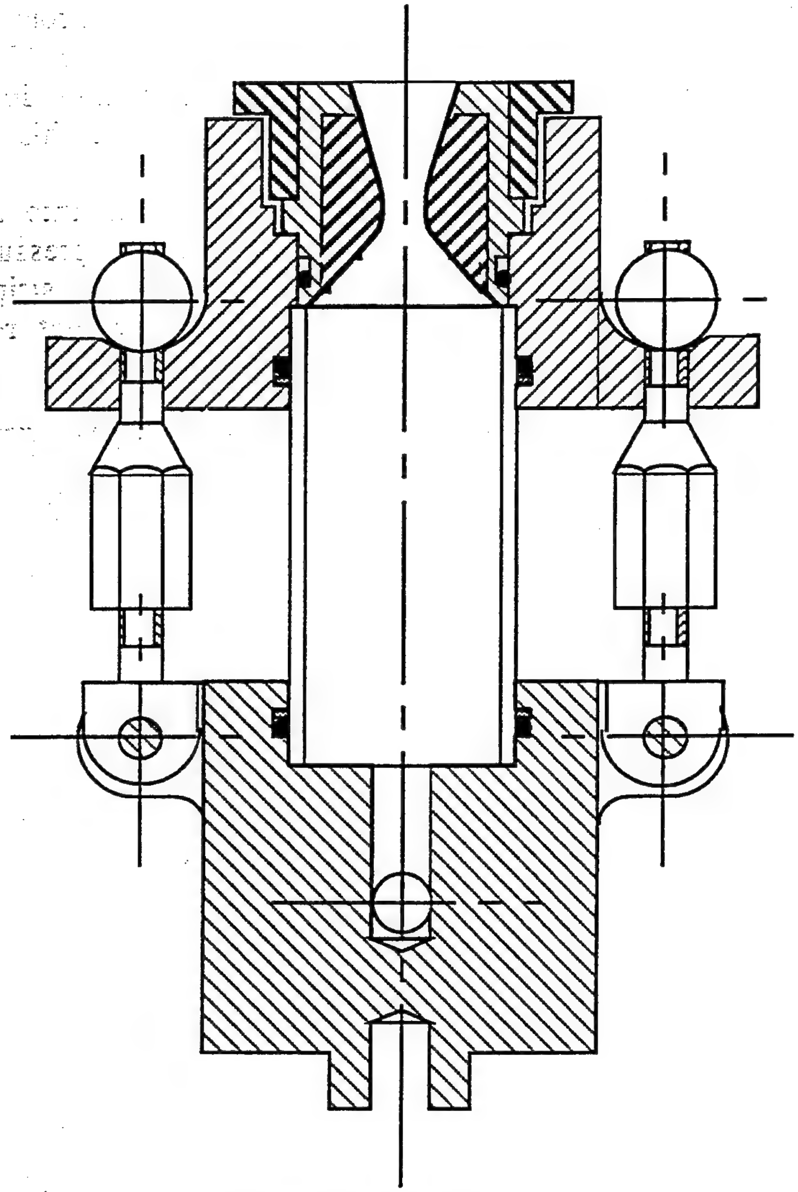


Fig. 5 TEST FIXTURE

With these requirements in mind, a mold was designed and built. The use of slides allowed the exterior wall to be a constant diameter. The slides were designed to operate mechanically. The molding machine opens the mold with a horizontal in-plane motion. To provide a horizontal out of plane motion, an angle pin is mounted in the stationary half of the mold, a corresponding angle hole is located in the slide on the moving half of the mold.(Figure 6) As the mold opens the pin causes the slide to move away from the part.

Keeping the part on the center line of the mold simplified all the molding functions. The gating is a combination of a disk and sprue gate. The sprue transports the plastic to the center line of the part. From there the plastic is pooled and turned 90 degrees to form a disk (Figure 12). This radial flow allows the plastic to flow smoothly and uniformly down the walls of the case. After molding, the case is machined to remove this disk and sprue.

For removal of the part a stripper ring was designed into the mold. A stripper ring pushes the part off of the core with uniform pressure to provided positive ejection of the part. However even with a stripper ring, the core did require draft in order to minimize the movement required by the stripper ring to release the part from the core.

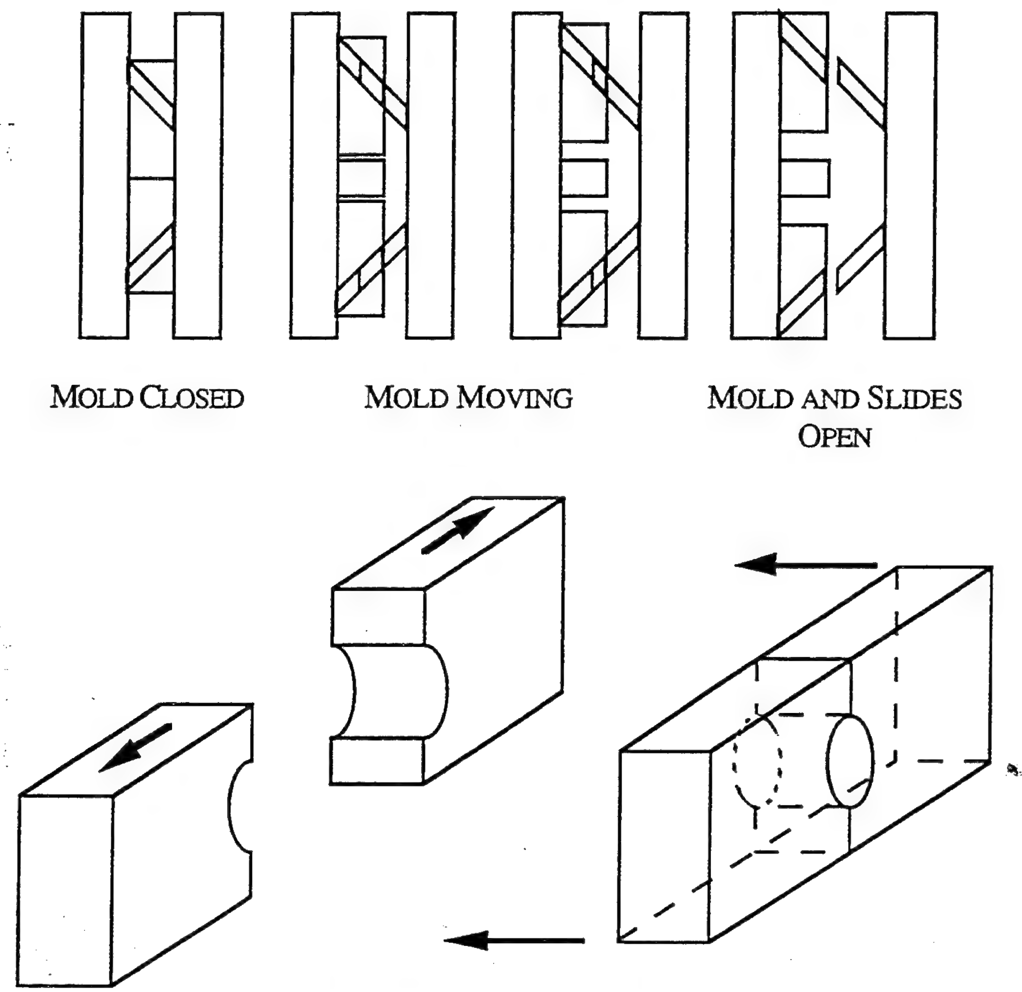
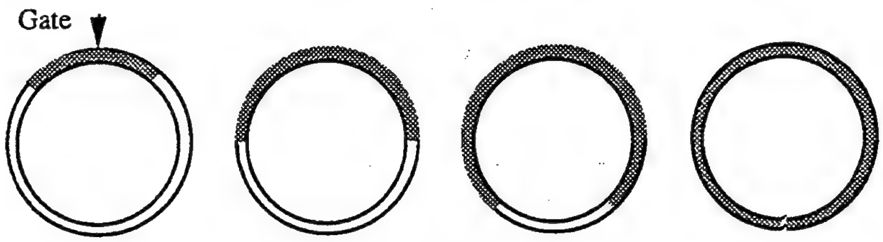


Fig. 6 MOVEMENT OF THE SLIDES

FLOW EFFECTS



FLOW OF A SIDE-GATED PART
Fig. 7

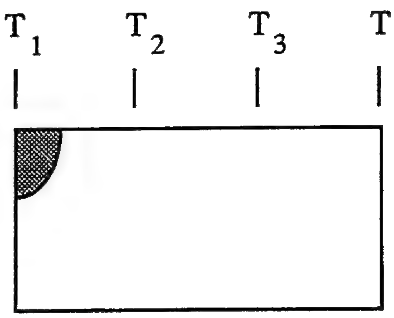


Fig. 8

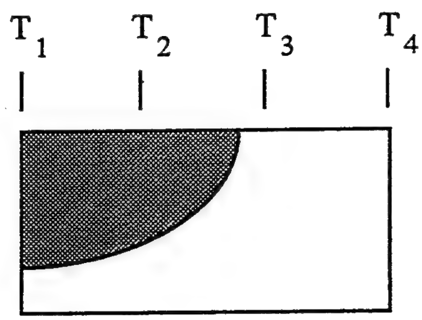


Fig. 9

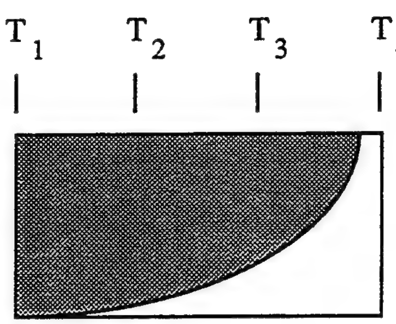


Fig. 10

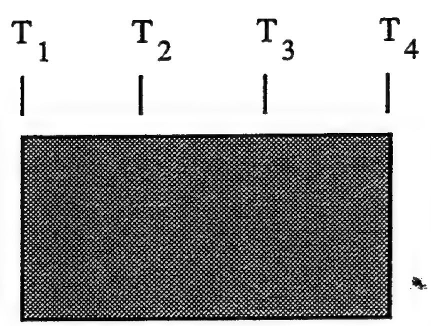
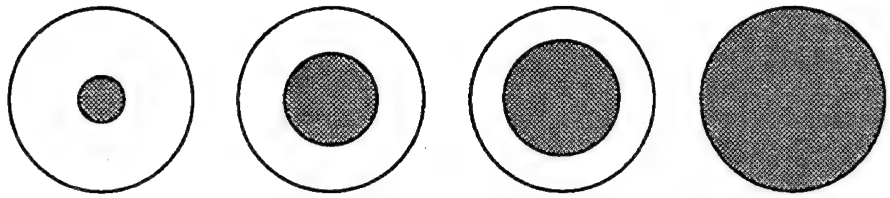


Fig. 11

The previous set of figures describes the flow through the part based on an edge gate on one side of the mold. The flow must separate (Figure 7) and flow around the core creating a weld or knit line on the opposite side of the part. Figures 7-11 describe flow from an edge gate that will create weld or knit lines. Weld lines or knit lines are typically much lower in strength than the parent material. For this reason the concept of a side gate could not be considered, and a combination disk-sprue gate was designed. Figure 12 describes a disk-gate fill pattern.



FLOW OF A CENTER GATED PART
Fig. 12

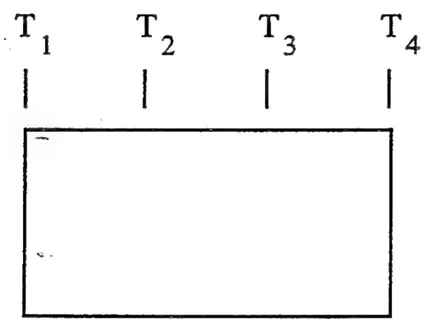


Fig. 13

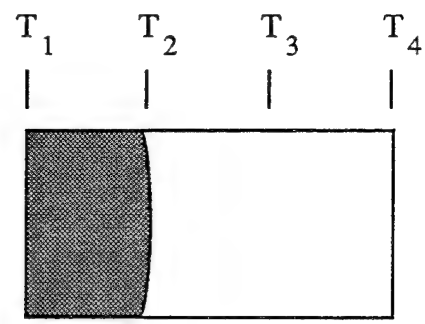


Fig. 14

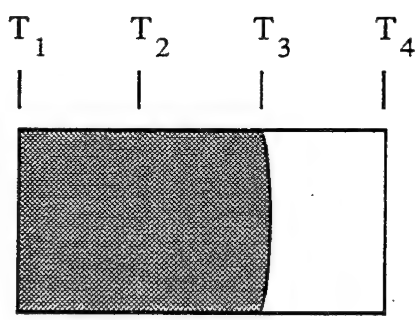


Fig. 15

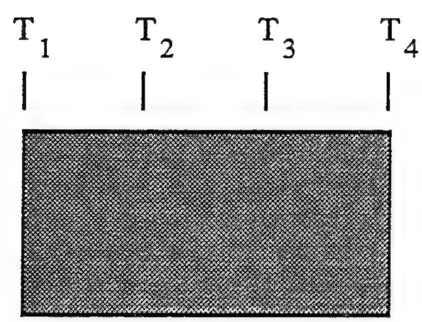


Fig. 16

After the disk is initially filled, the flow develops fully around the core and flows evenly down the walls of the core, producing a stronger part. This also allows molecular orientation as well as fiber orientation longitudinally along the part. This orientation does not provide for the hoop stress, but is far superior to having a weld line that would seriously lower the hoop strength. By comparing the two sets of flows in Figures 7 & 12 one can see that the disk gate minimizes the opportunity for weld lines to be created. Figures 12-16 describe flow from a disk gate that will negate weld or knit lines.

PROCESSING

Once a mold for the 2X4 motors was built, an injection molding process had to be developed using current commercial data, and information based on previous test results. The resulting molding process cycle is described below and follows the manufacturers recommendations.

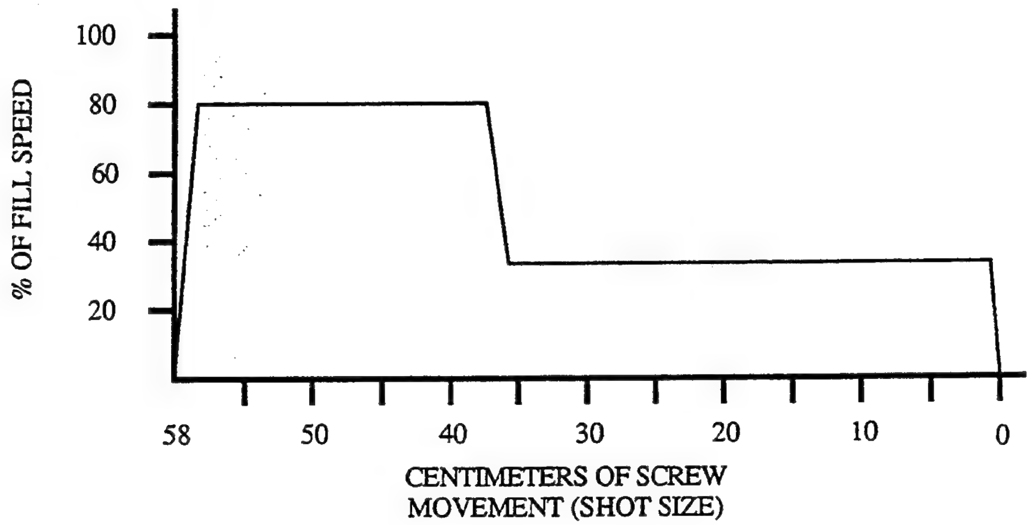


Fig. 17 FILL PROFILE FOR BOTH VECTRA MATERIALS

Figure 17 is the set-up profile for the molding machine at Hill AFB used to mold the 2X4 cases used in this project.

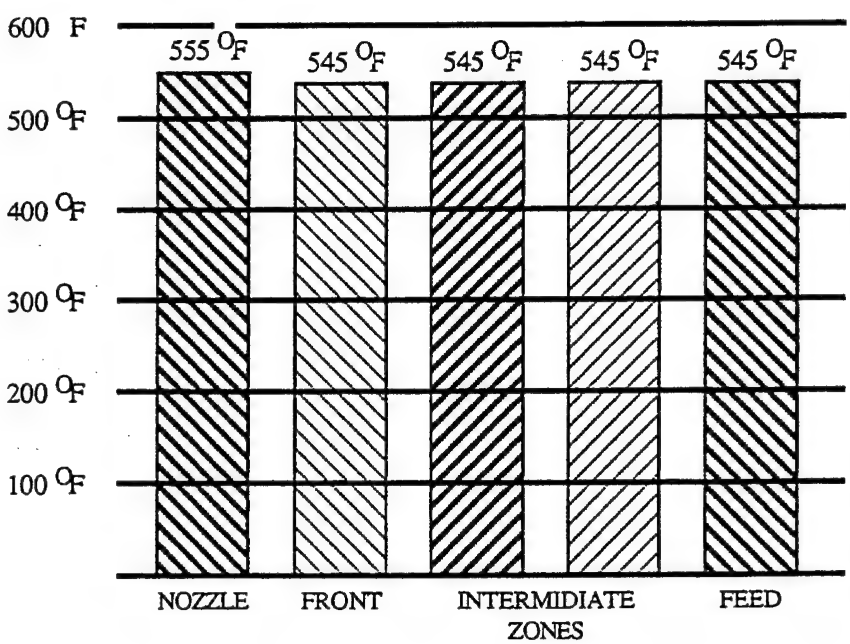


Fig. 18 VECTRA A-625 MOLDING TEMPERATURES

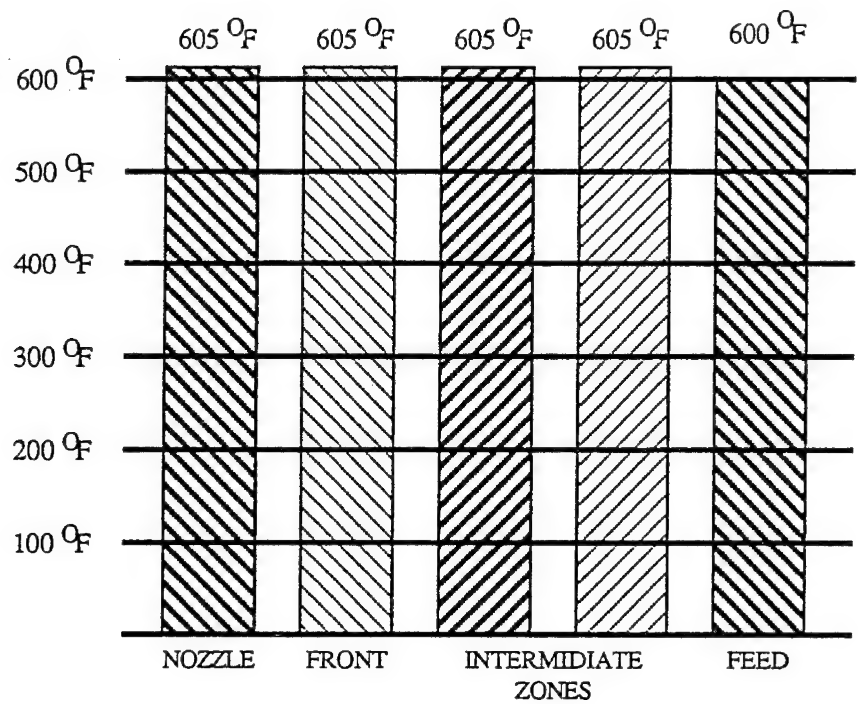


Fig. 19 VECTRA C-130 MOLDING TEMPERATURES

THE RESULTS

Compared with typical injection molding runs, a relatively small number of articles (approx. 50 of each material) were produced . For this reason a fully developed process may not have been achieved. This may have resulted in the production of articles with less strength than was mathematically predicted. In spite of this, the results remain quite impressive for a thermoplastic. Eleven motors were tested, of which seven survived the testing relatively undamaged. Pressures up to 1018 psi and temperatures of up to 2,000 degrees F. were contained during tests. The articles tested were molded of VECTRA A-625, VECTRA C-130, and RYTON. Preliminary tests were run for compatibility with the solid fuels and they were found to bond very well to the plastic, with no degradation of the plastic after bonding. These results make the use of plastic motor cases appear quite promising.

Fig. 20 COMPARISON OF STEEL AND PLASTIC CASES

The Figure 20 shows four of the 2X4 motor cases. On the left is a standard 2X4 metal case, immediately to the right is a VECTRA C-130 case, followed by a VECTRA A-625, and finally one that was machined from a solid piece of CELAZOLE. This last case is made of a material that is a lyotrope version of LCPs and mentioned previously. The wall thickness of this last motor is 1/4", as compared to 1/8" walls for the injection molded versions.

Fig. 21 POST FIRED PLASTIC CASES

As you can see in Figure 21 the post fired cases display little or no damage from the burning fuel. A char layer has been generated and acts as an insulator for the material. Table 2 reports the results of the first eleven motors tested.

FIRING NUMBER	CASE MATERIAL	PEAK PRES. (psi)	AVERAGE PRES. (psi)	DURATION (SEC.)	CASE/PROPELLANT BOND PROMOTER	COMMENTS
1	VECTRA C-130	961	864	1.446	N-100	
2	VECTRA C-130	1278		.070	NONE	FAILED ON IGNITION
3	VECTRA C-130	1018	990	1.376	NONE	
4	VECTRA C-130	1303		.059	N-100	FAILED ON IGNITION
5	VECTRA A-625	966				FAILED ON IGNITION
6	VECTRA A-625	1019				FAILED ON IGNITION
7	VECTRA A-625	862	818	1.436	NONE	
8	VECTRA A-625	913	876	1.419	NONE	
9	RYTON	316	269	2.346	NONE	
10	RYTON	753	727	1.578	N-100	
11	RYTON	745	713	1.605	NONE	

TEST FIRING RESULTS
TABLE 2

Results of these early tests shows success, seven of the eleven tested cases did well with pressures up to 1018 psi. The other four clearly did not meet the expectations of the initial designs. From the published values for tensile strengths of these materials, the expected pressures would be about twice as high as these. The heat generated during the tests proved to have little effect on the performance. This assumption is based on the video taped results of the test firings. When one of the motors burned through the side wall, the case continued to support the heavy steel portion of the test fixture that contains the nozzle.(top of Figure 5) We now believe that for this application the process dependency of the material is <u>much</u> more significant than first assumed. With subsequent runs the process should be refined and predicted design results should be obtained. The materials run to date have been limited to the Celanese VECTRA resins but Amoco XYDAR resins have been obtained and will soon be added to the test results.

Fig. 22 F-16 STORES LOCATIONS

With the initial results available at this time, the project is continuing to move toward the ambitious goal of developing an air-to-air missile case or a short range motor similar to that on the AIM-9L side winder. This missile is typically carried on a wing tip of a F-16, and can experience temperatures from -45 F to 145 F as well as loads up to 35 Gs. There is currently a cooperative project with the Air Force Institute of Technology at Wright Patterson AFB directed by the AFAL. The goal of this project is to design a short range air-to-air motor case using LCP materials that can be mounted on the F-16 wing tip location.(Figure 22)

CONCLUSION

Liquid Crystal Polymers graphically displayed that they can take the heat of a small solid fuel motor during limited operation. This capability is critical to the success of any application associated with a solid rocket motor. The LCPs have shown that strong fibers can be formed when drawn. The test results in Table 1 show that there is the possibility of obtaining high strength fibers under the right conditions. The LCPs proved that they can be molded easily, although the process must be well controlled to get the ultimate strength from material.

The work presented in this paper would not have been possible without the help and support of the following people:

Richard Griffen Doug Bennit, Hill AFB; John Rusek, J. Shelley, James Chew AFAL Edwards AFB; The Air Force Advanced Composites Program Office McClellan AFB; and Deborah Frank

This paper could not have been completed without their efforts.

Memo For Record 27 February 1991

APC Report: Hybrid Nozzle Demonstrator (HND)

1. Test firings were accomplished during the week of August 28, 1990 with the HND outfitted with a copper nozzle. The nozzle was instrumented with five thermocouples. The tests were analyzed to determine the convection heat transfer coefficient, h_g, and the throat wall temperature, T_{wg}. Since T_{wg} is directly related to the temperature of the gas in the chamber, T_g, the chamber gas temperature had to be established. The determination of T_{wg} came from applications of ISP, a thermochemical computer program obtained from Curt Selph. Numerous mixture weight iterations were used to understand how T_g varied as a function of the mixture weight. It was observed that the chamber gas temperature settles to approximately 1500 deg R over a six degree order of magnitude change in the mixture ratio. Therefore, it was assumed that T_g was known with a value of approximately 1500 deg R. The convection coefficient, h_g, was calculated using a laminar boundary layer correlation, which produced a value of approximately 200 Btu/ft^2*sec*deg F. The correlation was developed by Schoenman and Block of Aerojet Corp., Sacramento, CA, in AIAA report 67-447, 1967. A Lotus 123 spreadsheet was written by Bernard Bornhorst that used the two above numbers (i.e, 1500 and 200) to produce a model of the thermal environment. Graphical output shows a correlation between the experimental data and the model with a T_g of 1400 deg R (see figure #1). The discrepancy between temperatures values of 1400 and 1500 deg R for T_g as was expected comes from the fact that the thermocouple was not reading the throat wall temperature. The thermocouple was reading a temperature value *inside* of the copper nozzle, which has a temperature lag of around 100 deg R from the gas temperature. It can, however, be seen in figure one that the curves of the experimental data and the T_g of both 1500 and 1400 deg R lie within the same family of curves.

2. Currently, further HND testing has been delayed to obtain new fuel grain material. The acrylic used in the August firings

tended to bubble as the combustion occurred. The acrylic rod used was extruded. A cast acrylic rod has been ordered to investigate if it bubbles during the combustion cycle. The prime important of stopping the bubbling effect is to decrease the amount of acrylic that goes unburned and adheres to the nozzle. It is believed that the cast acrylic will not coat the nozzle in the same fashion. However, it will have to be tested to be certain.

3. The LCP nozzles have been injected molded at Hill AFB, Utah. The polymers that were injected were: Vectra A950, HX-4000, XYDAR SRT 300 and XYDAR SRT 500. These injected nozzles will be subjected to testing after the properties of the cast acrylic rod are determined. The main thrust of the testing schedule will be to establish the erosion properties of the polymers as a function of time. Annealing tests have also been added to the test matrix. The specifics behind the annealing testing have not been established as of yet, however. The prime factor in the tests will obviously be not to exceed the melting temperature of the materials with oven times as long as possible.

Eric E. Schmidt
Hybrid Nozzle Demonstrator Task Manager

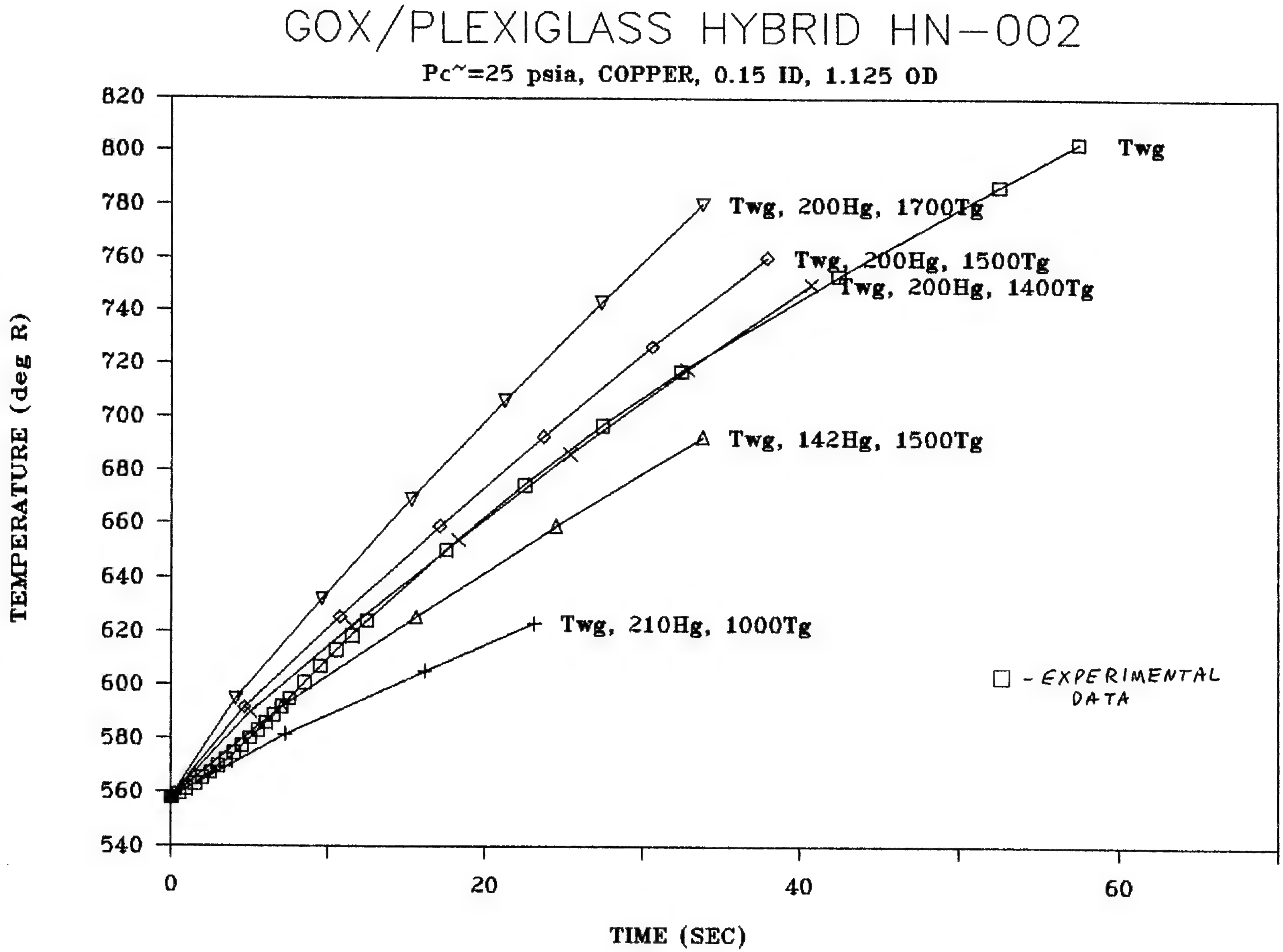

GOX/PLEXIGLASS HYBRID HN—002
Pc~=25 psia, COPPER, 0.15 ID, 1.125 OD
TEMPERATURE (deg R)
820
800
780
760
740
720
700
680
660
640
620
600
580
560
540
0
20
40
60
TIME (SEC)
Twg
Twg, 200Hg, 1700Tg
Twg, 200Hg, 1500Tg
Twg, 200Hg, 1400Tg
Twg, 142Hg, 1500Tg
Twg, 210Hg, 1000Tg
- EXPERIMENTAL DATA

FIGURE: 1

Memo for Record

Subject: Test Data from the Firings of Two Stainless Steel and Two Liquid Crystal Polymer Case Motors

For your information the temperature and pressure measurements from firing four 2x4 motors are sent to you. The experimental procedure did not work out completely as planned, but some of the measurements may be useful. Two of the motors which were fired had stainless steel cases, and two had liquid crystal polymer cases. Figure 1 is a drawing showing the test motor configuration. Parameters specific for each motor are given in Table 1.

The measurements of the chamber pressure and outside wall temperature of the case are attached. In addition the results of a program called ISP which estimates things such as chamber temperature, chamber gas density, choked throat gas velocity, etc. for the solid propellant used in these motors is also included.

The next two paragraphs contain a synopsis of what occurred during the firing of each motor to make the attached results more understandable.

The first stainless steel cased motor was fired at a nominal 200 psi for 15 seconds while the second motor was fired at nominal 400 psi for 12 seconds. During the firing as the outside of the wall became hot, the thermocouples began to become unglued, the contact between the thermocouple and the case became poorer, and the thermocouple measured a lower temperature than was actual. Only the thermocouple TC1, shown on Figure 1, on the motor fired nominally at 200 psi for 15 seconds remained well bonded for the whole test. By careful examination of the temperature ramp, it may be possible to see the temperature where the other thermocouples began to lose contact. Sorry the results aren't more accurate.

Both of the Vectra case motors burst before the grain burned out. The thermocouples on the Vectra cases were bonded with better contact to the case outer wall than they had been on the stainless steel cases. Temperature measurements on the Vectra cases should be relatively accurate with good case to thermocouple contact before the case burst. The char depth and char heat of reaction and their affect on the wall temperature distribution is unknown as yet. Further testing is underway to measure the char characteristics on Vectra A950, a neat resin.

For more information contact Capt Andrew Kenny, DSN 255-5296, Fax: DSN 255-5527.

cc: RKBR (John Rusek)
Chris Frank
Major Robinson

Motor Label	Case Material	Port Dia. (in)	Throat Dia. (in)	End Depth (in)	Wall Thickness (in)	Approx. Pressure (psi)	Approx. Burn Time (sec)
41	347 SS	.5	.147	.32	.125	200	15
42	347 SS	1.23	.100	.25	.125	380	12
21306	A 625	.5	.147	1.6	.121	320	3
21304	C 130	.5	.165	1.6	.121	210	4.6

Table 1. First Test Phase Motor Parameters

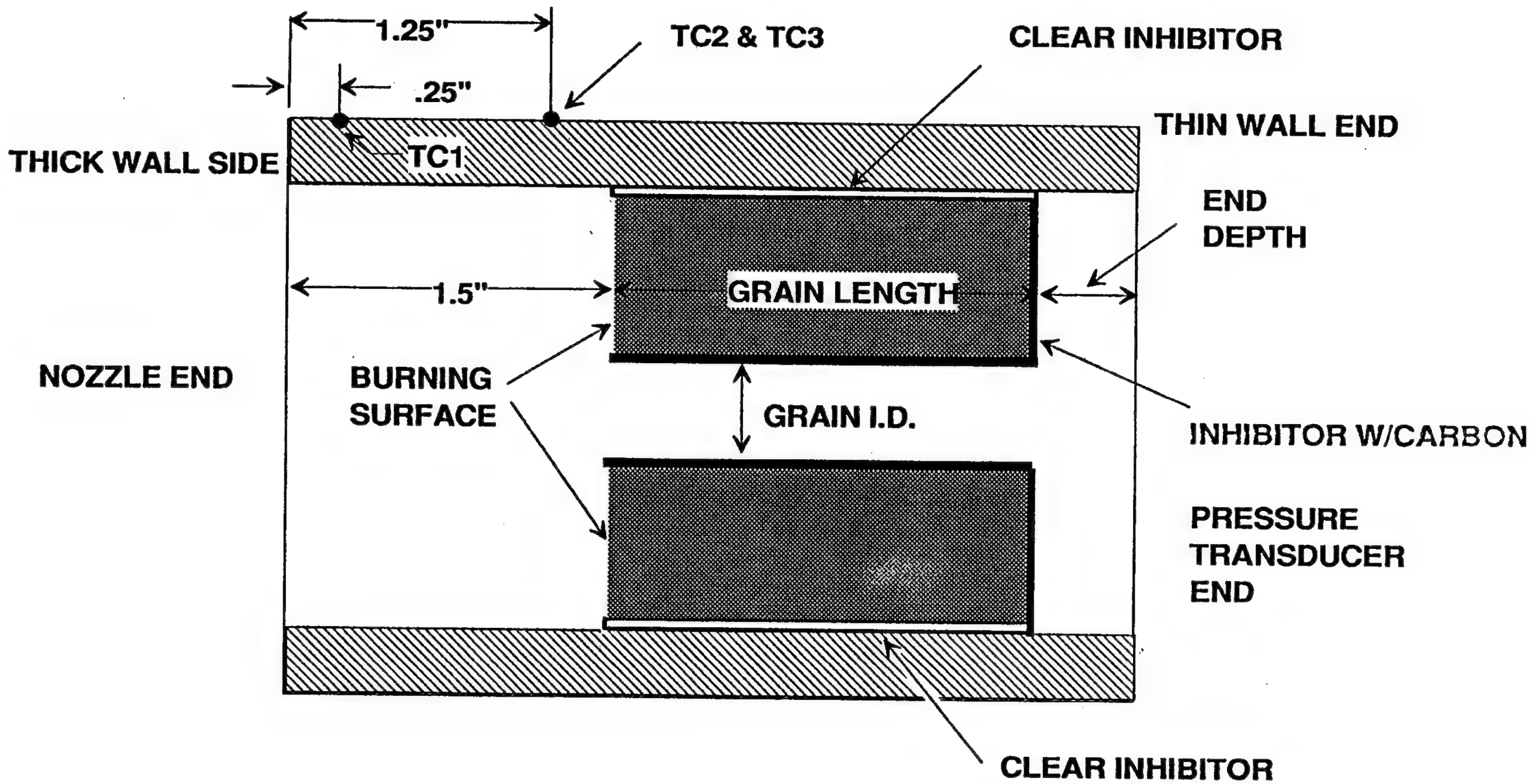


FIGURE 6. THERMOCOUPLE PLACEMENT AND GRAIN DIMENSIONS ON 2x4 MOTORS

Pressure Data First Stainless Steel Case #41

TIME (SEC)	PC1	PC2	IPC1	IPC2
*************	TIME OF DAY	[illegible]:29.994	**************	
0.000	-1.6248	-1.6845	0.0000	0.0000
0.200	-1.4879	-1.6845	-0.3113	-0.3369
0.400	-1.3511	-1.8211	-0.5952	-0.6875
0.600	-1.3511	-1.6845	-0.8654	-1.0380
0.800	-1.6248	-1.[illegible]479	-1.1530	-1.3613
1.000	[illegible]	[illegible]	-1.4879	-1.6845
1.200	[illegible]	-1.5479	-1.81[illegible]	-2.0078
1.400	-1.4879	-1.6845	-2.1242	-2.3310
1.600	-1.4879	-1.6845	-2.4217	-2.6679
1.800	[illegible]	-1.5479	-2.7193	-2.9912
2.000	-1.6248	-1.5479	-3.0306	-3.3008
2.200	-1.2143	-1.0015	-3.3145	-3.5557
2.400	-1.0775	-0.5917	-3.5437	-3.7151
2.600	-0.0302	2.0037	-3.7044	-3.5739
Ignition → 2.800	104.4132	122.8761	5.6637	8.9162 ←
3.000	195.9479	198.0270	36.7200	41.0085
3.200	201.4205	202.9447	75.4553	81.1056
3.400	204.9782	205.4963	117.0967	122.0496
3.600	209.0829	210.3212	158.5030	163.7316
3.800	209.3566	210.4578	200.3469	205.8094
4.000	210.0407	211.2774	242.2866	247.9829
4.200	210.3143	211.6872	284.3220	290.2793
4.400	210.8616	211.6872	326.4397	332.6169
4.600	212.5403	213.4630	368.7898	375.1318
4.800	212.9140	213.7362	411.3452	417.8518
5.000	212.9140	213.8728	453.9230	460.6128
5.200	213.3245	214.1460	496.5520	503.4148

TEST IDENTIFICATION = 2X4E6 RUN#12367 41S1 DATE (M/D/

TIME (SEC)	FC1	FC2	IPC1	IPC2
5.400	213.4613	214.4192	539.2305	546.2712
5.600	211.8194	212.6434	581.7585	588.9775
5.800	212.5035	213.4630	624.1909	631.5881
6.000	211.9562	212.7800	666.6370	674.2126
6.200	212.2299	213.1898	709.0554	716.8096
6.400	212.6403	213.1898	751.5425	759.4475
6.600	211.8194	212.3702	793.9885	802.0034
6.800	211.2721	211.8238	836.2978	844.4231
7.000	211.2721	211.8238	878.5523	886.7878
7.200	210.9985	211.9604	920.7793	929.1663
7.400	211.4089	212.3702	963.0200	971.5994
7.600	212.2299	212.9166	1005.3840	1014.1280
7.800	212.6403	213.7362	1047.8710	1056.7930
8.000	211.5458	212.5068	1090.2900	1099.4180
8.200	210.7248	211.4140	1132.5170	1141.8100
8.400	211.1353	212.0970	1174.7030	1184.1610
8.600	210.7248	211.4140	1216.8890	1226.5120
8.800	210.1775	210.7310	1258.9770	1268.7270
9.000	210.1775	211.0042	1301.0140	1310.9000
9.200	209.7671	210.3212	1343.0090	1353.0330
9.400	209.4934	210.4578	1384.9350	1395.1110
9.600	209.3566	210.0480	1426.8200	1437.1610
9.800	208.9461	209.6382	1468.6500	1479.1300
10.000	208.1252	209.0918	1510.3580	1521.0030
10.200	207.8515	208.4088	1551.9550	1562.7530
10.400	206.4833	207.1793	1593.3590	1604.3120
10.600	206.3465	207.1793	1634.6720	1645.7480
10.800	204.7046	205.4035	1675.7770	1687.0060

TIME (SEC)	PC1	PC2	IPC1	IPC2
11.000	205.2519	205.8133	1716.7720	1728.1280
11.200	203.4732	203.9009	1757.6450	1769.0990
11.400	202.9259	203.4911	1798.2850	1809.8380
11.600	203.6100	204.0375	1838.9390	1850.5910
11.800	202.9259	203.4911	1879.5920	1891.3440
12.000	204.2941	204.9937	1920.3140	1932.1930
12.200	205.1151	[illegible]	1961.2550	1973.2590
12.400	204.8414	205.5401	2002.2510	2014.3810
12.600	205.6624	206.4963	2043.3010	2055.5850
[illegible]	206.7569	207.5892	2084.5430	2096.9930
13.000	206.7569	207.7257	2125.8950	2138.5250
[illegible]	208.3988	209.6382	2167.4100	2180.2610
13.400	208.9461	209.7748	2209.1440	2222.2030
13.600	208.5356	209.6382	2250.8930	2264.1440
13.800	208.5356	209.3650	2292.6000	2306.0440
14.000	206.3465	207.1793	2334.0880	2347.6990
14.200	207.0306	207.8623	2375.4260	2389.2030
14.400	207.0306	207.8623	2416.8820	2430.7750
14.600	207.1674	207.8623	2458.2510	2472.3480
14.800	207.5779	208.4088	2499.7260	2513.9750
15.000	204.9762	205.8133	2540.9810	2555.3970
15.200	206.7569	207.5892	2582.1550	2596.7380
15.400	207.0306	207.5892	2623.5340	2638.2550
15.600	206.2097	206.9061	2664.8580	2679.7050
15.800	206.4833	207.3159	2706.1270	2721.1270
16.000	[illegible]	207.7257	2747.4640	2762.6310
16.200	206.7569	207.7257	2788.8290	2804.1750
16.400	206.6201	207.7257	2830.1690	2845.7230

TEST IDENTIFICATION = 2X4EB RUN#12367 41S1 DATE (M/D/

TIME (SEC)	PC1	PC2	IPC1	IPC2
16.600	207.1674	208.1356	2871.5470	2887.3080
16.800	206.7569	207.4525	2912.9390	2928.8660
17.000	208.5356	209.6382	2954.4670	2970.5750
17.200	184.8652	184.9133	2993.8070	3010.0290
17.400	143.1342	139.5615	3026.6090	3042.4790
17.600	110.9807	107.5968	3052.0200	3067.1940
17.800	91.0045	87.9261	3072.2180	3086.7460
18.000	75.2276	[illegible]	3088.9410	3102.8690
18.200	45.9897	42.7110	3101.1630	3114.4710
18.400	25.4662	22.4939	3108.3090	3120.9920
18.600	18.7619	13.2050	3112.7320	3124.5620
18.800	14.9309	9.3802	3116.1010	3126.8210
Burn out 19.000	12.4680	7.0380	[illegible]	3128.4640 ← Bur
19.200	10.8262	5.9652	[illegible]	[illegible]
19.400	9.7316	5.2821	3123.2260	3130.8920
19.600	8.6370	4.4625	3125.0630	3131.8660
19.800	7.9529	4.0527	3126.7220	3132.7170
20.000	7.5424	3.6429	3128.2710	3133.4870
20.200	7.2688	3.3697	3129.7520	3134.1880
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20.600	6.4478	2.8233	3132.4680	3135.4270
20.800	6.1742	2.5501	3133.7300	3135.9650
21.000	5.9005	2.4135	3134.9380	3136.4610
21.200	5.9005	2.5501	3136.1180	3136.9570
21.400	5.6269	2.4135	3137.2710	3137.4540
21.600	5.4901	2.4135	3138.3630	3137.9360
21.800	5.3532	2.1403	3139.4670	3138.3920
22.000	5.2164	2.1403	3140.5240	3138.8200

TEST IDENTIFICATION = 2X4EB RUN#12367 4181 DATE (M/D/

Temperature Data / First stainless steel Case #41

TIME (SEC)	TC1	TC2	TC3	
*****************	TIME OF DAY	12:52:29.994	**************	
0.000	68.6530	68.7585	68.8672	
0.200	68.5693	68.8422	68.8253	
0.400	68.6530	68.7585	68.7834	
0.600	68.6530	68.7585	68.7415	
0.800	68.6112	68.6747	68.7834	
1.000	68.6112	68.7585	68.7415	
1.200	68.6112	68.8422	68.7834	
1.400	68.6530	68.7585	68.8253	
1.600	68.6530	68.6747	68.8253	
1.800	68.6112	68.8422	68.8253	
2.000	68.6949	68.8422	68.9090	
2.200	68.6949	68.7585	68.9928	
2.400	68.7368	68.9259	69.0766	
2.600	68.7368	69.0096	69.1604	
2.800	68.6949	69.0933	69.3280	← Ignition
3.000	68.7787	69.2608	69.4117	
3.200	68.9462	69.4282	69.5793	
3.400	68.9462	69.5957	69.7887	
3.600	69.1555	70.0143	70.0820	
3.800	69.3230	70.4329	70.4590	
4.000	69.4905	70.9352	71.2130	
4.200	69.6161	71.6887	72.0927	
4.400	69.9092	72.6933	73.4332	
4.600	70.2860	73.8654	75.1088	
4.800	70.7048	75.2050	77.1614	
5.000	71.1235	76.7957	79.5910	
5.200	71.5840	78.5538	82.2301	

TEST IDENTIFICATION = 2X4EB RUN#12367 41S1 DATE (M/D/

Temperature Data, 1st Stainless Steel Case

TIME (SEC)	TC1	TC2	TC3
5.400	72.1284	80.5632	85.3719
5.600	72.7983	82.7399	88.7650
5.800	73.5101	85.1678	92.2838
6.000	74.2220	87.5957	95.8771
6.200	75.1013	90.2748	99.6068
6.400	75.9387	93.1213	103.3363
6.600	76.9017	95.9560	107.1470
6.800	77.7066	98.7107	111.6063
7.000	79.0791	101.7895	116.3089
7.200	80.3352	104.9493	121.4979
7.400	81.5495	107.9470	126.5653
7.600	82.8475	111.1069	132.0381
7.800	84.3130	114.5097	137.2271
8.000	85.7366	117.9126	142.5783
8.200	87.2859	121.2345	147.6862
8.400	88.9189	124.7994	152.7941
8.600	90.5100	128.4453	157.7399
8.800	92.3523	132.3343	162.7262
9.000	94.1528	136.0613	167.5098
9.200	96.0229	140.0313	172.3350
9.400	97.9679	143.8393	177.1962
9.600	99.9535	147.8093	182.2524
9.800	102.0200	152.0224	187.2691
10.000	104.0866	156.2355	192.2463
10.200	106.2747	160.4486	197.2631
10.400	108.5439	164.9047	202.5168
10.600	110.9752	169.5229	207.8495
10.800	113.4064	173.9404	212.9452

TIME (SEC)	TC1	TC2	TC3
11.000	115.8782	178.3615	217.9225
11.200	118.5931	183.0983	223.1762
11.400	121.3485	187.8352	228.5484
11.600	124.1445	192.4931	233.6442
11.800	127.0215	197.1509	238.8584
12.000	130.1011	202.0457	244.2306
12.200	133.2617	206.8615	249.6029
12.400	136.4223	211.7562	254.8171
12.600	139.6235	216.4141	259.9917
12.800	143.0678	221.2299	265.4036
13.000	146.5526	226.0457	270.6572
13.200	149.9564	230.5457	275.7249
13.400	153.5627	235.2036	280.8484
13.600	157.4122	240.0194	286.1272
13.800	161.3833	244.7563	291.5613
14.000	165.3949	249.4142	296.7236
14.200	169.4470	253.9931	301.8860
14.400	173.8281	258.7300	307.1257
14.600	178.2503	263.5459	312.1716
14.800	182.6725	268.1248	317.1399
15.000	187.1737	273.0195	321.9529
15.200	191.9907	277.7710	326.9600
15.400	196.9657	282.5806	331.9670
15.600	201.8222	287.2349	336.7800
15.800	206.8367	291.8118	341.5542
16.000	212.0486	296.6213	346.5225
16.200	217.4185	301.2759	351.5295
16.400	222.6304	305.8528	356.2649

TEST IDENTIFICATION = 2X4EB RUN#12367 41S1 DATE (M/D/

TIME (SEC)	TC1	TC2	TC3	
16.600	227.8422	310.1968	361.0391	
16.800	233.4095	314.7737	365.6580	
17.000	239.0557	319.5056	370.4709	
17.200	244.5045	323.8499	374.8569	
17.400	250.1902	328.0388	379.2817	
17.600	256.0732	332.4604	383.3184	
17.800	262.0354	336.8821	387.1999	
18.000	267.9580	340.9160	390.3052	
18.200	273.9597	345.0273	393.2549	
18.400	280.0540	348.5183	[illegible]	
18.600	286.3777	351.9314	399.9311	
18.800	292.5078	355.1897	403.0361	
19.000	298.7542	358.6804	406.2578	← Burn Out
19.200	304.6899	358.2925	404.2783	
19.400	310.1992	353.0176	397.9514	
19.600	315.3591	350.2248	394.8853	
19.800	319.9761	348.2854	392.7893	
20.000	324.1272	346.8892	390.7708	
20.200	327.9683	346.5012	388.6360	
20.400	331.4211	346.2686	386.2295	
20.600	334.4084	345.8806	383.7065	
20.800	337.2407	345.4929	381.0671	
21.000	339.8013	344.7947	378.5442	
21.200	342.2844	344.0190	375.9050	
21.400	344.3794	343.1658	373.5762	
21.600	346.3579	342.1572	371.2085	
21.800	348.2590	341.0713	368.7632	
22.000	349.2884	340.0527	366.3567	

TIME (SEC)	TC1	TC2	TC3
22.200	351.3240	339.0542	363.8726
22.400	352.5266	338.0457	361.4272
22.600	353.7295	336.8821	359.1372
22.800	354.7380	335.9512	356.8081
23.000	355.6692	335.0205	354.7510
23.200	356.4839	334.1670	352.5386
23.400	357.1047	333.2363	350.4814
23.600	357.7256	332.2278	348.7349
23.800	358.2300	331.4519	347.2500
24.000	358.5791	330.6763	345.9790
24.200	358.8894	329.6677	344.8147
24.400	359.1609	328.7368	343.7666
24.600	359.3938	327.6509	342.8350
24.800	359.5491	326.5649	341.9812
25.000	359.7041	325.4788	341.0107
25.200	359.6653	324.2376	340.2344
25.400	359.5875	323.0740	339.4971
25.600	359.4714	321.9104	338.7595
25.800	359.3550	320.9021	337.9055
26.000	359.2385	320.1262	337.1682
26.200	359.0447	319.5056	336.4307
26.400	358.8506	318.9626	335.6931
26.600	358.6956	318.4197	334.9558
26.800	358.5791	317.9541	334.2571
27.000	358.2686	317.6438	333.6360
27.200	358.1135	317.4111	332.8984
27.400	357.9194	317.1008	332.3164
27.600	357.7644	316.7905	331.7729

TEST IDENTIFICATION = 2X4EB RUN#12367 41S1 DATE (M/D.

TIME (SEC)	TC1	TC2	TC3
27.800	357.4927	316.6355	330.8801
28.000	357.2212	316.4026	330.0652
28.200	357.0659	316.1699	329.5217
28.400	356.7944	315.9373	328.9783
28.600	356.5615	315.7822	328.5513
28.800	356.2512	315.6269	328.2019
29.000	356.0186	315.5493	327.9692
29.200	355.7856	315.3167	327.6587
29.400	355.5142	315.1616	327.5034
29.600	355.2036	314.8513	327.4258
29.800	354.8933	314.6184	327.2705
30.000	354.5442	314.3081	326.8047
30.200	354.1951	313.9978	326.1060
30.400	353.8845	313.7651	325.2910
30.600	353.6519	313.6877	324.6311
30.800	353.2251	313.5325	324.[illegible]
31.000	353.0698	[illegible]	[illegible].8218
31.200	352.6431	313.1445	323.[illegible]
31.400	352.3716	313.0671	322.9622
31.600	352.0222	312.9119	322.7292
31.800	351.6343	312.7568	322.5352
32.000	351.2852	312.6016	322.4187
32.200	350.9360	312.3689	322.3799
32.400	350.6646	312.0586	322.3022
32.600	350.2378	311.6706	322.3022
32.800	349.8496	311.3604	322.3022
33.000	349.5781	310.8950	322.3022
33.200	349.1514	310.4294	322.2634

TIME (SEC)	TC1	TC2	TC3
33.400	348.7634	309.9641	322.3022
33.600	348.3755	309.6538	322.1858
33.800	347.9487	309.3435	322.1470
34.000	347.5994	309.0332	322.0305
34.200	347.2502	308.7229	321.8752
34.400	346.8235	308.4126	321.2930
34.600	346.4744	308.1023	320.6333
34.800	346.1252	307.7144	320.0510
35.000	345.7373	307.2490	319.5464
35.200	345.3105	307.0164	318.6924
35.400	345.0000	306.6284	317.7998
35.600	344.5732	306.2405	316.9458
35.800	344.1853	306.0078	316.2471
36.000	343.9138	305.6975	315.5098
36.200	343.5647	305.4648	314.9275
36.400	343.0991	305.2322	314.4228
36.600	342.7498	304.9993	313.8406
36.800	342.5171	304.6890	313.2974
37.000	342.2068	304.4563	312.6374
37.200	341.7800	304.2236	311.8611
37.400	341.4695	303.9910	310.6191
37.600	341.1204	303.7583	309.1440
37.800	340.7712	303.5254	307.4751
38.000	340.4221	303.2151	305.9614
38.200	340.1116	302.8274	304.1372
38.400	339.7620	302.5171	302.4680
38.600	339.4521	302.2068	300.7214
38.800	339.0254	301.8965	299.0913

TIME (SEC)	TC1	TC2	TC3
39.000	338.5986	301.4309	297.2668
39.200	338.2493	301.0430	295.2874
39.400	337.8613	300.7329	293.2690
39.600	337.5122	300.3450	291.0955
39.800	337.1631	300.0347	288.6890
40.000	336.7363	299.5693	286.1660
40.200	336.4648	299.4141	283.8760
40.400	336.0378	299.1038	281.5859
40.600	335.7664	298.7158	279.2959
40.800	335.3396	298.3281	277.1999
41.000	335.1069	298.0178	275.1428
41.200	334.6802	297.6299	273.3435
41.400	334.3308	297.2419	271.5659
41.600	333.9817	297.0093	269.5117
41.800	333.6326	296.6990	267.6157
42.000	333.2446	296.3110	265.5220
42.200	332.8955	295.9233	263.4285
42.400	332.5461	295.5354	261.3743
42.600	332.1582	295.3027	259.7549
42.800	331.8091	295.0698	258.4512
43.000	331.4988	294.8372	256.7527
43.200	331.1497	294.6821	254.[illegible]
43.400	330.8779	294.5269	252.4470
43.600	330.5288	294.2[illegible]	250.5509
43.800	330.1409	294.1392	248.9313
44.000	329.8691	293.9063	247.2327
44.200	329.5977	293.5959	245.4157
44.400	329.1709	293.1306	243.5986

TIME (SEC)	TC1	TC2	TC3
44.600	328.8994	292.8203	242.0185
44.800	328.5500	292.2773	240.2014
45.000	328.2009	291.9670	238.1474
45.200	327.8518	291.4238	235.8563
45.400	327.5803	290.9585	233.4467
45.600	327.1147	290.4155	231.0370
45.800	326.8042	290.0276	228.9040
46.000	326.5327	289.4846	226.6524
46.200	326.1060	289.0190	224.5587
46.400	325.8730	288.6313	222.5047
46.600	325.4851	288.3210	220.6086
46.800	325.1360	287.9331	218.9495
47.000	324.8257	287.6228	217.4484
47.200	324.5928	287.3125	216.2239
47.400	324.2437	287.0798	215.0784
47.600	323.9333	286.6145	214.2093
47.800	323.7004	286.2266	213.5378
48.000	323.3125	285.5283	212.8267
48.200	323.1575	284.9854	211.9577
48.400	322.9246	284.3647	210.8912
48.600	322.5366	283.5115	209.5481
48.800	322.2263	282.9685	208.2840
49.000	321.9546	282.3479	206.8620
49.200	321.6443	281.7273	205.6374
49.400	321.4116	281.0291	204.3339
49.600	321.0623	280.2534	202.7933
49.800	320.7131	279.6328	201.1737
50.000	320.2864	278.7795	199.4752

TIME (SEC)	TC1	TC2	TC3
50.200	319.8984	277.8486	197.9346
50.400	319.5493	277.0728	196.5915
50.600	319.2002	276.2971	195.2880
50.800	318.7732	275.5212	194.0239
51.000	318.5405	274.6680	192.7994
51.200	318.1138	273.7300	191.6538
51.400	317.7646	272.9404	190.6268
51.600	317.4541	272.0720	189.7577
51.800	317.1826	271.2827	189.0072
52.000	316.8335	270.5720	188.0987
52.200	316.5232	270.0195	187.3481
52.400	316.2126	269.5459	186.5976
52.600	315.9023	268.8352	185.7286
52.800	315.5144	267.9668	[illegible]
53.000	315.2039	267.1772	183.6744
53.200	314.9324	266.3879	182.8844
53.400	314.5832	265.6772	[illegible]
53.600	314.3118	264.9668	181.0278
53.800	314.0012	264.3352	180.3958
54.000	313.6133	263.5459	180.0008
54.200	313.3806	262.9141	179.6453
54.400	313.1089	262.2827	179.3688
54.600	312.8374	261.5720	178.7367
54.800	312.5271	261.0195	178.1047
55.000	312.2942	260.2300	177.6702
55.200	312.0227	259.4404	177.2357
55.400	311.7122	258.6511	176.5642
55.600	311.4407	257.7827	175.9716

TIME (SEC)	TC1	TC2	TC3
55.800	311.1304	257.2300	175.3791
56.000	310.7810	256.6772	175.1816
56.200	310.5095	256.0457	174.8656
56.400	310.3542	255.4142	174.4706
56.600	309.9663	254.9405	174.1546
56.800	309.8889	254.3879	173.7595
57.000	309.5784	253.7563	173.0090
57.200	309.1904	253.2826	172.3745
57.400	308.9578	252.4931	172.0908
57.600	308.8025	252.0194	171.7671
57.800	308.4534	251.4668	171.6043
58.000	308.1816	251.0721	171.4421
58.200	307.9490	250.5984	171.4016
58.400	307.6387	250.3616	171.5232
58.600	307.4446	250.1247	171.9266
58.800	307.1731	249.9668	172.4151
59.000	307.0178	249.9668	173.0880
59.200	306.7463	249.8089	173.7595
59.400	306.5522	249.7299	174.0755
59.600	306.3970	249.5721	174.1546
59.800	306.2419	249.4931	174.4311
60.000	306.0479	249.2563	174.5496
60.200	306.0090	249.3352	174.7866
60.400	305.7375	249.4142	175.3001
60.600	305.6987	249.4142	175.8926
60.800	305.5435	249.4142	176.3666
61.000	305.3496	249.3352	176.4061
61.200	305.1943	249.3352	176.4852

TEST IDENTIFICATION = 2X4EB RUN#12088 (4282 DATE [illegible]

Pressure Data 2nd Stainless Steel Case Integrated

TIME (SEC)	PC1	PC2	IPC1	IPC2
5.400	2.3431	4.8723	0.9955	6.4214
5.600	4.2586	7.8776	1.6556	7.3964
5.800	5.5846	10.7462	2.7400	9.5588
6.000	8.2265	12.3304	4.2211	11.8720
Ignition → 6.200	15.8626	21.9475	6.6326	15.3053 ← Ig
6.400	99.7512	100.0013	18.1976	28.0001
6.600	185.[illegible]	189.0113	46.7560	57.4014
6.800	[illegible].5486	244.47[illegible]	89.5031	100.7498
7.000	287.1245	292.2822	142.5802	154.4252
7.200	331.2661	334.3555	20[illegible].6192	217.0357
7.400	[illegible].7051	356.2117	273.1162	285.1455
7.600	[illegible]	358.7791	345.1[illegible]	358.6448
7.800	365.1560	368.3674	418.3611	432.3596
8.000	367.3275	369.5986	491.7153	506.1562
8.200	370.5975	372.7405	565.4[illegible]	580.3901
8.400	373.3444	375.4727	[illegible].8882	655.2117
8.600	377.1015	379.4371	714.5526	730.7024
[illegible]	377.[illegible]	380.2037	790.4655	806.6711
9.000	379.4277	381.6176	866.2175	882.8564
9.200	380.9329	383.1223	942.2539	959.3328
9.400	383.2585	385.3079	1018.6730	1036.1760
9.600	383.1221	385.3079	1095.3110	1113.2370
9.800	384.7639	386.9470	1172.1000	1190.4630
10.000	383.8062	386.1274	1248.9570	1267.7700
10.200	382.9851	384.8960	1325.6360	1344.8730
10.400	384.2166	385.9910	1402.3560	1421.9620
10.600	385.3113	387.2202	1479.3090	1499.[illegible]30
10.800	384.7639	386.6738	1556.3180	1576.6730

TIME (SEC)	PC1	PC2	IFC1	IFC2
11.000	385.9954	387.7666	1633.3920	1654.1160
11.200	384.3535	386.4006	1710.4270	1731.5330
11.400	[illegible].9429	385.8542	1787.2570	1808.7590
11.600	383.8062	385.9910	1864.0320	1885.9430
11.800	382.5747	384.4883	1940.6700	1962.9910
12.000	383.8062	385.8542	2017.3080	2040.0250
12.200	383.1221	385.0347	2094.0010	2117.1140
12.400	384.4902	386.1274	2170.7620	2194.2310
12.600	384.4902	386.4006	2247.6600	2271.4830
12.800	385.4480	387.2202	2324.6540	2348.8450
13.000	384.9006	386.6738	2401.6880	2426.2350
13.200	385.4480	387.2202	2478.7240	2503.6240
13.400	384.9006	386.8105	2555.7580	2581.0260
13.600	384.2166	386.4006	2632.6700	2658.3490
13.800	384.7639	386.8105	2709.5680	2735.6700
14.000	381.6167	383.5320	2786.2060	2812.7040
14.200	382.3010	384.2151	2862.5980	2889.4790
14.400	384.6270	386.2642	2939.2910	2966.5270
14.600	386.5425	388.3130	3016.4080	3043.9840
14.800	389.8264	391.8647	3094.0450	3122.0020
15.000	391.4883	393.3674	3172.1740	3200.5260
15.200	393.1101	395.1431	3250.6320	3279.3770
15.400	395.2993	397.3289	3329.4720	3358.6240
15.600	396.1201	398.1484	3408.6150	3438.1720
15.800	398.4463	400.3340	3488.0720	3518.0200
16.000	386.8162	388.4497	3566.5960	3596.5970
16.200	381.8705	383.5320	3643.4660	3674.0740
16.400	380.5225	382.0295	3719.7120	3750.6550

TEST IDENTIFICATION = 2X4EB RUN#12368 4252 DATE (M/D/Y)

2nd Stainless Steel 21 Feb 91

TIME (SEC)	PC1	PC2	IPC1	IPC2
16.600	383.2588	384.8980	3796.0890	3827.3460
16.800	373.2708	374.7895	3871.7400	3903.3140
17.000	350.0107	350.8843	3944.0680	3975.8800
17.200	317.4468	317.6902	4010.8120	4042.7240
17.400	278.1787	276.8462	4070.3780	4102.1950
17.600	244.3833	242.6958	4122.6330	4154.1480
17.800	219.8920	218.2441	4169.0590	4200.2420
18.000	193.6219	192.0166	4210.4100	4241.2700
18.200	164.4786	162.7838	4246.2190	4276.7500
18.400	136.5666	134.7805	4276.3240	4306.5080
18.600	112.7594	111.0118	4301.2580	4331.0860
18.800	94.2883	92.5706	[illegible]	4351.4450
19.000	80.0587	78.3640	4339.3950	4368.5390
19.200	68.1551	66.7529	4354.2190	4383.0510
19.400	59.5352	57.8738	4366.9880	4395.5120
19.600	52.5572	50.9071	4378.1990	4406.3910
19.800	45.8529	44.2136	4388.0390	4415.9020
20.000	38.6013	36.9737	4396.4840	4424.0200
20.200	31.6233	29.8704	4403.5080	4430.7030
20.400	25.3294	23.7234	4409.2030	4436.0630
20.600	20.4038	18.6691	4413.7770	4440.3010
20.800	16.5727	14.0246	4417.4770	4443.5700
21.000	14.5204	11.0194	4420.5860	4446.0740
21.200	12.6048	8.8338	4423.2970	4448.0590
21.400	10.9630	7.7410	4425.6520	4449.7150 ← B
21.600	9.7316	6.7848	4427.7230	4451.1680 Burn out
21.800	8.9106	5.8286	4429.5860	4452.4300
22.000	8.3633	5.2821	4431.3130	4453.5390

Temperature Data 2nd Stainless Steel [illegible]

TIME (SEC)	TCI	[illegible]2	TC3	
5.400	72.4604	[illegible]	72.6343	
5.600	72.6697	75.2830	72.6762	
5.800	72.9210	75.5342	72.8019	
6.000	73.2979	[illegible]	72.8857	
6.200	73.5491	76.7064	73.0533	← Ignition
6.400	73.9678	77.5437	73.1789	
6.600	74.3028	78.4646	73.3465	
6.800	74.8472	79.4694	73.5560	
7.000	75.4753	80.8090	73.7654	
7.200	76.1871	82.2324	74.1424	
7.400	77.0246	84.0[illegible]4	74.6870	
7.600	77.9877	85.9164	75.6924	
7.800	79.1601	88.3445	75.9911	
8.000	80.4153	90.9400	78.7924	
8.200	81.9237	93.7868	81.0546	
8.400	83.6824	97.1673	83.6938	
8.600	85.6504	100.4894	86.7100	
8.800	87.9116	104.2167	90.1032	
9.000	90.1727	108.1060	93.7059	
9.200	92.7688	112.2384	97.6589	
9.400	95.3231	116.4517	101.5103	
9.600	98.2902	120.9082	105.7371	
9.800	101.4104	125.6078	110.1860	
10.000	104.6522	130.1453	114.6049	
10.200	107.9751	134.7538	119.1455	
10.400	111.7436	139.7065	123.9698	
10.600	115.3907	[illegible]	129.0374	
10.800	119.1187	149.6728	134.0239	

TEST IDENTIFICATION = 2X4EB RUN#12368 4262 DATE (M/D/Y

TIME (SEC)	TC1	TC2	TC3
11.000	123.0899	154.8585	139.0509
11.200	127.5474	160.3683	144.5239
11.400	132.1670	165.9592	150.0375
11.600	136.6650	171.2741	155.6726
11.800	141.6493	177.4950	161.5105
12.000	149.9564	183.7324	167.6321
12.200	158.1014	190.0487	173.9974
12.400	165.6791	196.2960	180.1204
12.600	172.8813	202.7601	186.4014
12.800	180.4625	209.7870	193.0380
13.000	187.2384	216.8728	199.9115
13.200	194.9537	224.3144	206.6271
13.400	202.1795	232.0518	213.4611
13.600	210.1161	240.1051	220.6507
13.800	217.7368	247.6846	227.9588
14.000	225.1996	254.8694	235.1089
14.200	232.6624	262.1331	242.5355
14.400	240.4410	269.2704	250.7522
14.600	248.9304	277.7026	259.4429
14.800	257.0645	284.8401	267.8569
15.000	264.6062	291.5894	275.8848
15.200	272.6218	298.3369	283.6091
15.400	280.2915	304.9331	290.9065
15.600	287.5081	310.9844	297.5051
15.800	294.9961	317.3459	303.7546
16.000	302.6394	324.0952	309.9263
16.200	310.1274	330.1465	315.9040
16.400	317.5381	335.8098	321.4158

TIME (SEC)	TC1	TC2	TC3
16.600	325.1425	342.0161	327.0442
16.800	332.7082	347.8347	332.6724
17.000	339.9246	353.6531	338.5501
17.200	346.8696	[illegible]	344.0066
17.400	353.3877	364.7471	349.4409
17.600	360.3328	369.7122	354.4092
17.800	367.8208	374.6772	359.2612
18.000	[illegible]	379.0991	363.8804
18.200	376.6568	383.5989	368.4995
18.400	377.0935	[illegible]	372.8857
18.600	378.5291	390.8137	377.3105
18.800	382.1375	[illegible]	373.4290
19.000	383.6118	380.3406	368.0725
19.200	384.5430	376.3064	363.3367
19.400	385.9009	372.5049	358.7173
19.600	387.3702	369.1689	354.4092
19.800	388.3840	366.2209	350.3726
20.000	389.7031	363.4282	346.5686
20.200	391.0610	360.7129	342.8420
20.400	[illegible]	358.2302	[illegible]
20.600	393.6606	355.9028	335.8940
20.800	394.2612	353.8063	332.7500
21.000	[illegible]	[illegible]	329.6448
21.200	396.1047	349.6189	326.7336
21.400	397.0747	347.6794	324.0940 ← Burn Out.
21.600	398.2000	345.7400	321.4934
21.800	399.0146	343.7229	318.7375
22.000	399.7902	341.9387	316.1370

TEST IDENTIFICATION = 2X4EB RUN#12370 21304 DATE (M/D/

Pressure Data Vectra C130 case

TIME (SEC)	PC1	PC2	IPC1	IPC2
******************	TIME OF DAY	10:22: 8.934	**************	
0.000	-2.0352	-1.5480	0.0000	0.0000
0.200	-2.0352	-1.6845	-0.4070	-0.3232
0.400	-1.8984	-1.4114	-0.8004	-0.6328
0.600	-2.1720	-1.5480	-1.2075	-0.9288
0.800	-2.1720	-1.2748	-1.6419	-1.2110
1.000	-2.0352	-1.5480	-2.0626	-1.4933
1.200	-1.8984	-1.5480	-2.4559	-1.8029
1.400	-2.0352	-1.4114	-2.8493	-2.0988
1.600	-2.1720	-1.4114	-3.2700	-2.3811
1.800	-2.0352	-1.2748	-3.6908	-2.6497
2.000	-1.7616	-1.2748	-4.0704	-2.9047
2.200	-2.0352	-1.1382	-4.4501	-3.1460
2.400	-1.6248	-0.4552	-4.8161	-3.3053
2.600	0.2904	3.3693	-4.9496	-3.0139
Ignition → 2.800	10.5503	18.1210	-3.8655	-0.8649 ← Igr
3.000	139.8257	142.5542	11.1721	15.2026
3.200	185.3799	197.2191	43.6926	49.1799
3.400	199.0598	201.0147	82.1366	87.0033
3.600	206.4470	208.3905	122.6874	127.9440
3.800	211.3717	213.0346	164.4692	170.0865
4.000	214.1077	215.9029	207.0171	212.9802
4.200	215.2021	216.8591	249.9481	256.2563
4.400	215.0653	216.5859	292.9749	299.6011
4.600	214.3813	216.1761	335.9194	342.8772
4.800	215.3389	216.7225	378.8914	386.1670
5.000	216.0229	217.6786	422.0276	429.6072
5.200	216.0229	217.5420	465.2324	473.1294

Pressure Data Vectra C130 case

TIME (SEC)	PC1	PC2	IPC1	IPC2
5.400	215.2021	216.5859	508.3550	516.5422
5.600	215.4757	216.9957	551.4226	559.9004
5.800	215.4757	216.8591	594.5178	603.2859
6.000	214.1077	215.3566	637.4763	646.5076
6.200	215.7493	216.9957	680.4619	689.7427
6.400	216.5701	218.0884	723.6939	733.2510
6.600	217.3909	218.9079	767.0898	776.9507
6.800	218.8957	220.4104	810.7187	820.8826
7.000	219.5797	220.9568	854.5662	865.0193
7.200	220.9477	222.3227	898.6189	909.3472
7.400	221.9053	223.5520	942.9041	953.9346
7.600	19.9895	17.8478	967.0735	978.0747
7.800	12.4655	9.6524	970.3391	980.8247
8.000	9.5927	6.9206	972.5449	982.4819
8.200	7.6775	5.2815	974.2720	983.7021
8.400	6.7199	4.4620	975.7117	984.6765
8.600	6.1727	3.7790	977.0010	985.5007
8.800	5.6255	3.3693	978.1809	986.2156
9.000	5.3519	3.0961	979.2786	986.8621
9.200	4.9415	2.9595	980.3079	987.4675
9.400	4.8047	2.6863	981.2825	988.0322
9.600	4.3943	2.4132	982.2024	988.5422
9.800	3.9840	2.2766	983.0403	989.0112
10.000	3.9840	2.2766	983.8372	989.4666
10.200	3.7104	2.0034	984.6067	989.8945
10.400	3.7104	1.8668	985.3489	990.2815
10.600	3.4368	1.7302	986.0635	990.6411
10.800	3.3000	1.7302	986.7371	990.9871

Case Burst → .cas

TEST IDENTIFICATION = 2X4EB RUN#12370 21304 DATE (M/D/

Temp Data Vectra C130 case

TIME (SEC)	TC1	TC2	TC3	
*****************	TIME OF DAY	10:22: 8.934	**************	
0.000	68.0512	70.0828	64.9165	
0.200	68.0931	69.9990	64.9165	
0.400	68.0931	70.0828	64.9165	
0.600	68.1350	70.0828	64.8746	
0.800	68.1350	70.0828	64.9165	
1.000	68.0931	69.9990	64.9165	
1.200	68.1769	70.0828	64.9584	
1.400	68.1350	70.0828	64.9165	
1.600	68.1350	70.0828	64.9165	
1.800	68.1350	70.0828	64.9584	
2.000	68.1350	69.9990	64.9584	
2.200	68.0931	70.0828	64.9584	
2.400	68.1769	70.0828	64.9584	
2.600	68.1350	70.1665	64.9584	← ignition
2.800	68.1350	70.0828	64.9584	
3.000	68.0931	70.1665	65.0003	
3.200	68.1350	70.1665	65.0003	
3.400	68.1769	70.1665	65.0841	
3.600	68.1350	70.2502	65.0841	
3.800	68.2187	70.3340	65.2098	
4.000	68.1769	70.3340	65.2098	
4.200	68.0931	70.5014	65.3355	
4.400	68.2187	70.5852	65.4193	
4.600	68.2187	70.7527	65.5450	
4.800	68.2187	70.8364	65.6706	
5.000	68.2606	71.0039	65.8801	
5.200	68.2606	71.1714	66.0896	

TEST IDENTIFICATION = 2X4EB RUN#12370 21304 DATE (M/D/

TIME (SEC)	TC1	TC2	TC3
5.400	68.3863	71.5063	66.3410
5.600	68.3863	71.8412	66.6762
5.800	68.3863	72.0087	67.0951
6.000	68.4700	72.5111	67.5141
6.200	68.5538	72.8461	68.0169
6.400	68.6375	73.3485	68.6453
6.600	68.6794	73.6835	69.3156
6.800	68.8469	74.3534	70.0279
7.000	68.9307	74.8558	70.7820
7.200	69.0982	75.4419	71.7456
7.400	69.2657	76.1955	72.6674
7.600	113.2375	122.3636	74.0081
7.800	122.4375	136.6259	75.3907
8.000	120.4921	151.9417	76.7313
8.200	120.2489	158.1005	78.0720
8.400	119.3978	160.0453	79.4965
8.600	118.0604	161.8281	80.7210
8.800	116.0851	163.7351	82.4292
9.000	116.1961	165.2316	83.9794
9.200	119.3573	178.4456	86.2418
9.400	121.5459	192.6588	94.5793
9.600	122.2754	191.4744	100.4507
9.800	123.9370	194.2381	104.6268
10.000	125.9229	202.7660	107.9110
10.200	129.9353	209.1619	113.2224
10.400	134.0287	215.1630	117.5609
10.600	140.4322	240.1151	121.8991
10.800	153.0771	268.5415	125.6678

7.71
case failure

TEST IDENTIFICATION = 2X4EB RUN#12369 21306 DATE (M/D/

Pressure Data Vectra A625 Case

TIME (SEC)	PC1	PC2	IPC1	IPC2
5.400	-1.6247	-1.5479	-9.6630	-8.8507
5.600	-1.6247	-1.4113	-9.9879	-9.1466
5.800	-1.6247	-1.4113	-10.3129	-9.4289
6.000	-1.4879	-1.4113	-10.6241	-9.7111
6.200	-1.2143	-0.5916	-10.8944	-9.9114
Ignition → 6.400	2.0696	4.8729	-10.8088	-9.4833 ⇐ Ig
6.600	150.3924	154.7380	4.4374	6.4778
6.800	292.1475	294.3569	48.6915	51.3874
7.000	311.4404	313.2097	109.0503	112.1440
7.200	316.9136	318.2544	171.8856	175.2914
7.400	319.2395	320.5869	235.5009	239.1765
7.600	320.4709	321.8164	299.4722	303.4170
7.800	321.4290	322.7727	363.6621	367.8757
8.000	322.9341	324.1387	428.0984	432.5669
8.200	324.5759	325.7781	492.8494	497.5586
8.400	326.2178	327.4175	557.9290	562.8784
8.600	326.9021	327.9639	623.2410	628.4165
8.800	327.9966	329.4668	688.7307	694.1594
9.000	329.5017	330.6963	754.4805	760.1758
9.200	331.1438	332.1990	820.5452	826.4656
9.400	335.2485	336.4341	887.1843	893.3289 — Co
Case Burst → 9.600	13.2155	16.4850	922.5308	928.6208
9.800	12.[illegible]	8.6981	925.6128	931.1392
10.000	10.1426	6.1024	927.8877	932.6191
10.200	8.5006	4.5997	929.7520	933.6895
10.400	7.6796	4.0532	931.3699	934.5547
10.600	6.8587	3.3701	932.8237	935.2971
10.800	6.3114	2.9603	934.1406	935.9302

TEST IDENTIFICATION = 2X4EB RUN#12369 21306 DATE (M/D/

Temperature Data Vectra A625 Case

Black

Ther

TIME (SEC)	TC1	TC2	TC3	
5.400	74.0876	74.8644	74.5556	
5.600	74.2133	74.9481	74.6394	
5.800	74.3389	75.1993	74.7650	
6.000	74.4227	75.2830	74.8908	
6.200	74.5902	75.4505	75.0164	
Ignition → 6.400	74.6739	75.7016	75.1840	← Ignition
6.600	74.7158	75.8691	75.3097	
6.800	74.9252	76.0365	75.4354	
7.000	75.0508	76.2040	75.6449	
7.200	75.2183	76.5389	75.8124	
7.400	75.3439	76.8738	75.9800	
7.600	75.4695	77.2087	76.1895	
7.800	75.5789	77.3762	76.3990	
8.000	75.8883	77.7111	76.7341	
8.200	76.0558	78.1297	77.0274	
8.400	76.2233	78.5484	77.3625	
8.600	76.4746	78.8833	77.8234	
8.800	76.6840	79.4694	78.3620	
9.000	77.1446	80.0555	78.9127	
9.200	77.3959	80.6416	79.5411	
Case Burst → 9.400	77.6471	81.3114	80.2533	← Case Failure
9.600	86.6924	109.0783	80.5047	
9.800	86.6086	105.8095	81.6358	
10.000	87.1949	103.4875	81.8872	
10.200	89.1631	101.9479	82.9765	
10.400	89.7493	101.2997	83.8144	
10.600	90.3775	100.2464	84.9455	
10.800	90.8800	99.7602	85.9929	

PA

PA

The ASTRONAUTICS LABORATORY Theoretical ISP Program
Micro Version by Beckman & Acree   Revision: 5/89   16:16:23 22-Ja

PROPELLANT	HF	DENSITY	WEIGHT	MOLES	VOLUME
R-45M	-2.9700	.9000	9.5300	.0952	10.5889
DOZ	-246.0000	.9100	2.0000	.0048	2.1978
AL	.0000	2.7000	3.0100	.1116	1.1148
AP	-70.6900	1.9500	83.2100	.7082	42.6718
DDI	-206.3000	1.1010	2.2500	.0040	2.0436

GRAM ATOMS / 100 GRAMS
AL .1116 C .9649 CL .7082 H 4.3701 N .7163 O 2.8659

ENTHALPY = -52.37376   DENSITY =1.706
CSTAR (FT/SEC)= 5025.422

	CHAMBER	THR(SHIFT)	EXH(SHIFT)	EXH(SHIFT)
PRESSURE (PSIA)	200.000	115.077	14.6960	.299347
EPSILON	.000000	1.00000	2.84119	49.9999
ISP	.000000	103.217	209.008	285.980
ISP (VACUUM)	.000000	193.091	241.617	297.669
TEMPERATURE(K)	2933.25	2742.72	2039.31	1001.14
MOLECULAR WEIGHT	25.3726	25.5620	25.8687	25.8921
MOLES GAS/100G	3.94125	3.91205	3.86568	3.86218
CF	.000000	.660818	1.33812	1.83091
PEAE/M (SECONDS)	.000000	89.8746	32.6098	11.6894
GAMMA	1.21120	1.21120	1.22322	1.26324
HEAT CAP (CAL)	44.9163	44.5842	42.0974	36.8319
ENTROPY (CAL)	252.072	252.072	252.072	252.072
ENTHALPY (KCAL)	-52.3740	-64.6127	-102.558	-146.326
DENSITY (G/CC)	.14346E-02	.88938E-03	.15459E-03	.64200E-05
ITERATIONS	22	20	47	91

MOLES/100 GRAMS

ALCL	.00047	.00021	.00000	.00000
ALCLO	.00120	.00058	.00000	.00000

PA(

The ASTRONAUTICS LABORATORY Theoretical ISP Program PA
Micro Version by Beckman & Acree Revision: 5/89 16:16:23 22-Ja

PROPELLANT	HF	DENSITY	WEIGHT	MOLES	VOLUME
R-45M	-2.9700	.9000	9.5300	.0952	10.5889
DOZ	-246.0000	.9100	2.0000	.0048	2.1978
AL	.0000	2.7000	3.0100	.1116	1.1148
AP	-70.6900	1.9500	83.2100	.7082	42.6718
DDI	-206.3000	1.1010	2.2500	.0040	2.0436

GRAM ATOMS / 100 GRAMS
AL .1116 C .9649 CL .7082 H 4.3701 N .7163 O 2.8659

ENTHALPY = -52.37376 DENSITY =1.706
CSTAR (FT/SEC)= 5039.064

CHAMBER THR(SHIFT) EXH(SHIFT) EXH(SHIFT)

PRESSURE (PSIA)	400.000	228.816	14.6960	.594423
EPSILON	.000000	1.00000	4.55440	49.9997
ISP	.000000	104.168	229.644	286.215
ISP (VACUUM)	.000000	193.762	255.851	297.852
TEMPERATURE (K)	2973.59	2767.28	1802.10	997.495
MOLECULAR WEIGHT	25.4709	25.6353	25.8881	25.8917
MOLES GAS/100G	3.92604	3.90087	3.86279	3.86224
CF	.000000	.665101	1.46625	1.82746
PEAE/M (SECONDS)	.000000	89.5947	26.2075	11.6375
GAMMA	1.20985	1.21023	1.22886	1.26345
HEAT CAP (CAL)	44.9818	44.6265	41.2177	36.8086
ENTROPY (CAL)	246.655	246.655	246.655	246.654
ENTHALPY (KCAL)	-52.3733	-64.8386	-112.956	-146.480
DENSITY (G/CC)	.28412E-02	.17578E-02	.17507E-03	.12795E-04
ITERATIONS	7	19	29	28

MOLES/100 GRAMS

ALCL	.00041	.00017	.00000	.00000
ALCLO	.00104	.00048	.00000	.00000
ALCL2	.00035	.00017	.00000	.00000
ALCL3	.00016	.00011	.00000	.00000
ALHO	.00006	.00002	.00000	.00000
ALHO2	.00067	.00027	.00000	.00000
ALO	.00002	.00000	.00000	.00000
CCLO	.00002	.00001	.00000	.00000
CHO	.00001	.00001	.00000	.00000
CO	.66568	.65134	.56561	.31164
CO2	.29919	.31357	.39929	.65327
CL	.03809	.02602	.00055	.00000
CLH	.66716	.68092	.70769	.70824
CLHO	.00005	.00002	.00000	.00000
CLO	.00005	.00002	.00000	.00000
CL2	.00012	.00007	.00000	.00000
H	.03593	.02369	.00050	.00000
HO	.03884	.02160	.00009	.00000

HO2	.00001	.00000	.00000	.00000
H2	.42727	.42694	.49658	.75050
H2O	1.38639	1.39485	1.33431	1.08041
H3N	.00001	.00001	.00000	.00000
NO	.00359	.00170	.00000	.00000
N2	.35636	.35731	.35816	.35816
O	.00198	.00075	.00000	.00000
O2	.00258	.00099	.00000	.00000
AL2O3 (ALPHA)	.00000	.00000	.05578	.05578

FURTHER TESTING OF **VECTRA** 2x4 MOTOR CASES

Hieu T. Nguyen
United States Air Force
Astronautics Laboratory

Further Testing of Vectra 2x4 Motor Cases

Earlier firings of 2x4 motors demonstrated the concept of using advanced polymer cases. Several maximum pressure / burn time combinations were determined. By building upon the data gained from these earlier tests, new tests to get quantitative estimates on char rates, heat transfer parameters, and practical working temperatures will be made. The test results will be analyzed and put in a short report.

New cases have been made with twice the old wall thickness. The first few new firings will be made with motors with stainless steel cases and cast with end burning grains and instrumented with thermocouples as well as the usual pressure transducer. The thermocouple readings will be used in conjuntion with ISP program generated hot chamber gas properties to verify the calculated thermal gradient in the wall of the steel and Vectra cases. The gradient calculations will be done with a simple 1-D computer program. Figure 1is an example.

Table 1 shows what the significant stresses are throughout the standard thin walled case and pressures at which it failed in the previous radial and end burning tests. Table 2 shows similar information for the new thick walled cases, though both tables are of limited utility because they are based on the assumption that the whole case wall has the same modulus, i.e. is at the same temperature. Putting it all together, safe firing pressure/time combinations will be estimated from the thermocouple measurements, ISP program information, and the previous work where several cases ruptured at times and temperatures which were measured.

It will be attempted to set the grain dimensions so that it will be possible to measure ablation and char versus heat transfer rate while holding the average

axial gas velocity approximately constant. Similarly the ablation and char rate could be measured versus axial gas velocity while holding the heat transfer rate constant. Ablation and char depth will also be correlated with burn time. Figures 2 thru 5 illustrate the correlations which hopefully will be possible, although the plot shapes are unknown as yet and just sketched for illustrative purposes.

Table 3 shows for the new thick wall 2x4 cases all the possible pressure, temperature, and velocity combinations with the available 2x4 nozzle throat diameters and possible range in burning surface area. Table 4 shows similar information for the standard thin wall motor case. Table 5 in conjunction with Figure 6 shows the saliant motor characterstics for the first phase of testing. Hg in these tables stands for the relative heat transfer coefficient, but at this stage it is only possible to estimate it in relative terms based upon convection as in Equation 1.

$$Hg(2)=Hg(1) * \{K(2)/K(1)\}^{.6} *\{D(1)/D(2)\}^{.2} *\{U(1)/U(2)\}^{.4} *\{V(2)/V(1)\}^{.8} *\{P(2)/P(1)\}^{.8} *\{Cp(2)/Cp(1)\}^{.4} \quad \text{EQN 1}$$

Hg(2)= relative change from Hg(1) based upon:

K(1) and K(2)--gas conductivity in first and second cases

D(1) and D(2)--chamber diameter which is same in both cases

U(1) and U(2)--gas viscosity in first and second cases

V(1) and V(2)--average gas velocity in first and second cases

P(1) and P(2)-- chamber pressures in first and second cases

Cp(1) and Cp(2)--gas heat capacity in first and second cases

Comparing Equation 1 with Tables 2 and 3 it is evident that the only ways to significantly change the convective heat transfer affecting the 2x4 cases are by varying axial velocity and chamber pressure via the throat diameter and burning

surface area. A more accurate value of this number would include the effects of radiation and conduction. These effects will be better known after the first phase of testing and used in setting the grain dimensions of the motors to be fired in the second phase.

Attatchment 1 at the end of this package shows the procedure to be used.

STAINLESS STEEL

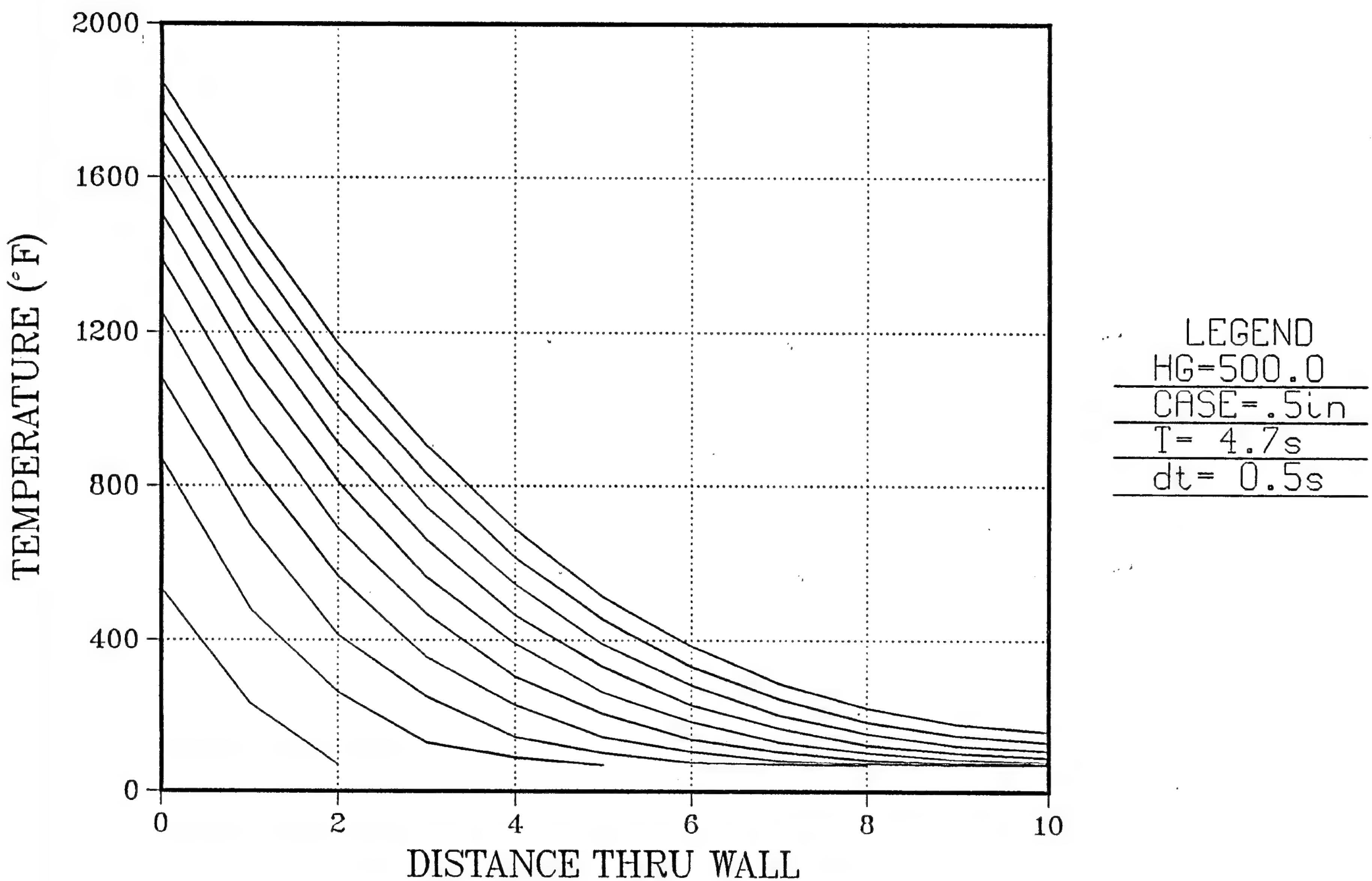


Figure 1. Computer Code Generates the Same Time Transient Temperature Gradients as Sutton example. Half Inch Wall, hg = 500 Btu/hr-ft-F

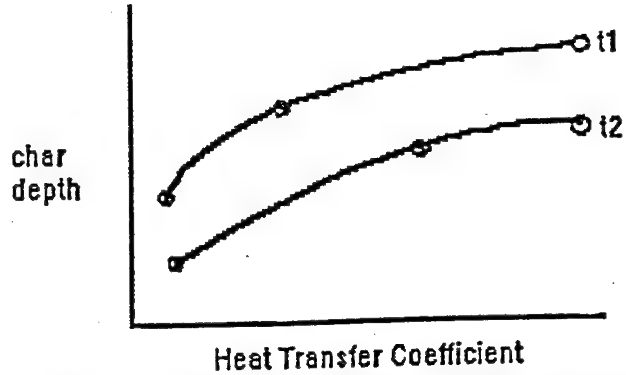


Figure 2. Char Depth/ Ablation Depth Vs Heat Input Rate

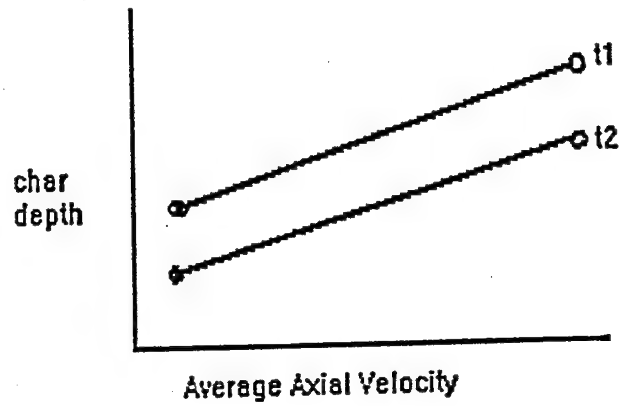


Figure 3. Ablation and Char vs Velocity for two Burn Times.

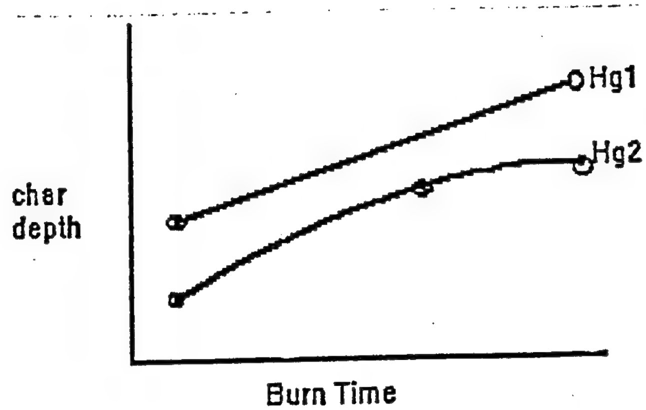


Figure 4. Ablation and Char Depth Vs Burn Time at Constant Hg

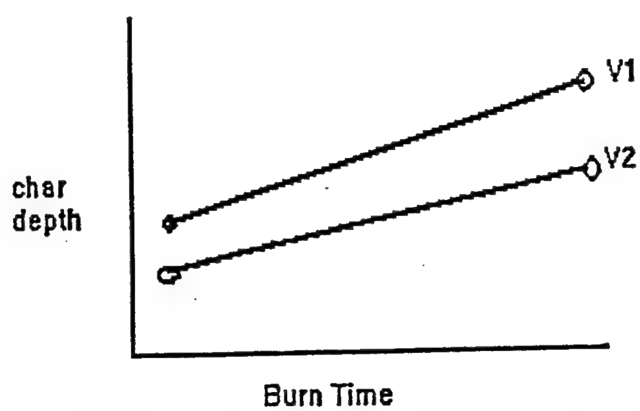


Figure 5. Char Depth/ Ablation Depth Vs Time at Constant Velocity

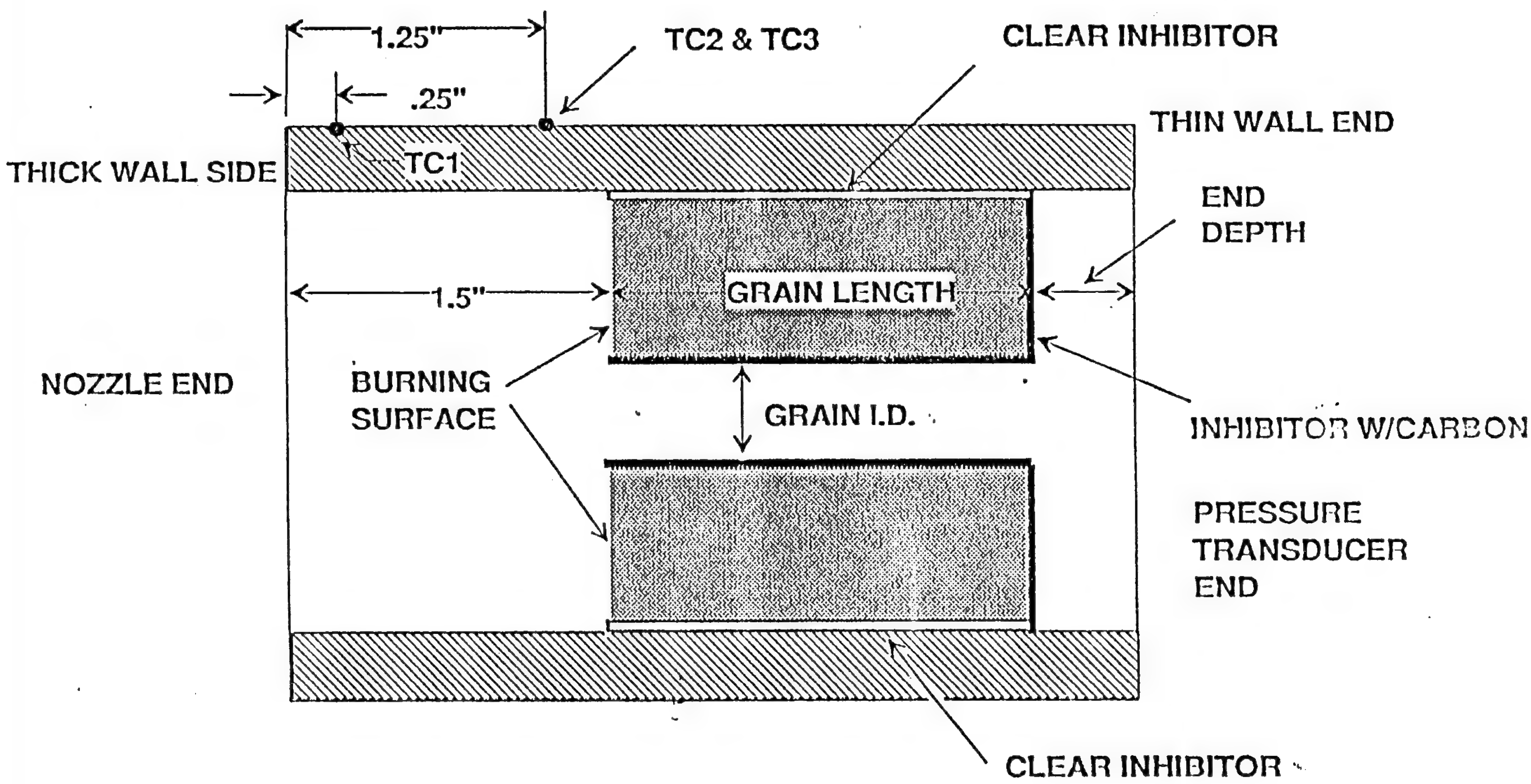


FIGURE 6. THERMOCOUPLE PLACEMENT AND GRAIN DIMENSIONS ON 2x4 MOTORS

	A	B	C	D	E	F	G	H	I
1				TABLE 1					
2		PRESSURE VS STRESS IN STANDARD THICKNESS 2X4 CASES							
3									
4		1.123	is I.R. (a)	1.244	is O.R. (b)	0.121	is thickness (t)		
5									
6	PRESSURE		S-TAN-a	S-TAN-b	S-RAD-a	S-RAD-b	T-a	T-b	
7	(psi)		(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	
8	50		490	440	-50	0	270	220	
9	150		1,471	1,321	-150	0	810	660	
10	200		1,961	1,761	-200	0	1,081	881	
11	250		2,452	2,202	-250	0	1,351	1,101	
12	300		2,942	2,642	-300	0	1,621	1,321	
13	350		3,432	3,082	-350	0	1,891	1,541	
14	400		3,923	3,523	-400	0	2,161	1,761	
15	500		4,903	4,403	-500	0	2,702	2,202	
16	600		5,884	5,284	-600	0	3,242	2,642	
17	700		6,865	6,165	-700	0	3,782	3,082	
18	800		7,845	7,045	-800	0	4,323	3,523	
19	900		8,826	7,926	-900	0	4,863	3,963	
20	1,000		9,807	8,807	-1,000	0	5,403	4,403	
21	1,200		11,768	10,568	-1,200	0	6,484	5,284	
22	1,400		13,729	12,329	-1,400	0	7,565	6,165	
23	1,600		15,690	14,090	-1,600	0	8,645	7,045	
24	1,800		17,652	15,852	-1,800	0	9,726	7,926	
25	2,000		19,613	17,613	-2,000	0	10,807	8,807	
26	2,200		21,574	19,374	-2,200	0	11,887	9,687	
27	2,400		23,536	21,136	-2,400	0	12,968	10,568	
28	2,600		25,497	22,897	-2,600	0	14,049	11,449	
29	2,800		27,458	24,658	-2,800	0	15,129	12,329	
30	3,000		29,420	26,420	-3,000	0	16,210	13,210	
31									
32		OUTLINED FIGURES SHOW MAXIMUM PRESSURE AND CASES STRESSES							
33	WITHSTOOD BY VECTRA A625 AFTER 10 SECONDS EXPOSURE TO HEAT AT 200 PSI								
34	AND AFTER 2 SECONDS AT 1000 PSI.								
35									
36	PRESSURE = INTERNAL CHAMBER PRESSURE								
37	S-TAN-a = HOOP STRESS AT INSIDE WALL								
38	S-TAN-b = HOOP STRESS AT OUTSIDE WALL								
39	S-RAD-a = RADIAL COMPRESSIVE STRESS AT INSIDE WALL								
40	S-RAD-b = RADIAL STRESS AT OUTSIDE WALL								
41	T-a = SHEAR STRESS AT INSIDE WALL								
42	T-b = SHEAR STRESS AT OUTSIDE WALL								
43									

	A	B	C	D	E	F	G	H
1				TABLE 2				
2		PRESSURE VS STRESS IN MODIFIED THICK 2X4 CASES						
3								
4		0.994	is I.R. (a)	1.244	is O.R. (b)	0.25	is thickness (t)	
5								
6	PRESSURE		S-TAN-a	S-TAN-b	S-RAD-a	S-RAD-b	T-a	T-b
7	(psi)		(psi)	(psi)	(psi)	(psi)	(psi)	(psi)
8	50		227	177	-50	0	138	88
9	150		680	530	-150	0	415	265
10	200		906	706	-200	0	553	353
11	250		1,133	883	-250	0	691	441
12	300		1,360	1,060	-300	0	830	530
13	350		1,586	1,236	-350	0	968	618
14	400		1,813	1,413	-400	0	1,106	706
15	500		2,266	1,766	-500	0	1,383	883
16	600		2,719	2,119	-600	0	1,660	1,060
17	700		3,172	2,472	-700	0	1,936	1,236
18	800		3,625	2,825	-800	0	2,213	1,413
19	900		4,079	3,179	-900	0	2,489	1,589
20	1,000		4,532	3,532	-1,000	0	2,766	1,766
21	1,200		5,438	4,238	-1,200	0	3,319	2,119
22	1,400		6,345	4,945	-1,400	0	3,872	2,472
23	1,600		7,251	5,651	-1,600	0	4,425	2,825
24	1,800		8,157	6,357	-1,800	0	4,979	3,179
25	2,000		9,064	7,064	-2,000	0	5,532	3,532
26	2,200		9,970	7,770	-2,200	0	6,085	3,885
27	2,400		10,876	8,476	-2,400	0	6,638	4,238
28	2,600		11,783	9,183	-2,600	0	7,191	4,591
29	2,800		12,689	9,889	-2,800	0	7,745	4,945
30	3,000		13,596	10,596	-3,000	0	8,298	5,298
31								
32								
33	PRESSURE = INTERNAL CHAMBER PRESSURE							
34	S-TAN-a = HOOP STRESS AT INSIDE WALL							
35	S-TAN-b = HOOP STRESS AT OUTSIDE WALL							
36	S-RAD-a = RADIAL COMPRESSIVE STRESS AT INSIDE WALL							
37	S-RAD-b = RADIAL STRESS AT OUTSIDE WALL							
38	T-a = SHEAR STRESS AT INSIDE WALL							
39	T-b = SHEAR STRESS AT OUTSIDE WALL							

	A	B	C	D	E	F	G	H
1			GAS PROPERTIES IN 2X4 MOTORS					
2								
3			TABLE 3. THICK WALL CASES					
4								
5	Pmax	Pmin	burn rate	throat dia	I.D. grain	TEMP	V Chambr	Hg
6	(psi)	(psi)	(in/sec)	(in)	(in)	F	(ft/sec)	(relative)
7								
8	200	179.4667	0.145	0.126	0.604258	4852	14.54997	1
9	200	179.3586	0.145	0.125	0.645605	4852	14.31993	0.987332
10	200	178.7766	0.145	0.12	0.817935	4852	13.19725	0.924905
11	200	175.5103	0.145	0.1	1.25496	4852	9.164757	0.690887
12	300	266.6998	0.17	0.1	1.006842	4895	9.166903	0.955788
13	400	358.2719	0.19	0.1	0.719849	4924	9.172724	1.203741
14	450	404.253	0.1975	0.1	0.514206	4935	9.180446	1.323571
15	500	450.2366	0.205	0.1	0.17016	4946	9.18727	1.440826
16								
17								
18								
19			TABLE 4. THIN WALL CASES					
20								
21	P	burn rate	throat dia	I.D. Grain	TEMP	V Chambr	Hg	mass flo
22	(psi)	(in/sec)	(in)	(in)	F	(ft/sec)	(relative)	(relative)
23								
24	200	0.145	0.145	0.60513	4852	14.92769	0.960595	1.393427
25	200	0.145	0.138	0.891915	4852	13.52119	0.887479	1.262136
26	200	0.145	0.125	1.239553	4852	11.09371	0.757543	1.035543
27	200	0.145	0.12	1.342377	4852	10.22396	0.709645	0.954356
28	200	0.145	0.1	1.659989	4852	7.099972	0.530092	0.662747
29	300	0.17	0.125	0.783248	4895	11.0963	1.048001	1.54501
30	300	0.17	0.12	0.97536	4895	10.22635	0.981738	1.423882
31	300	0.17	0.1	1.471337	4895	7.101634	0.733341	0.988807
32	400	0.19	0.12	0.447415	4924	10.23285	1.236424	1.892387
33	400	0.19	0.1	1.281875	4924	7.106144	0.923586	1.314158
34	500	0.205	0.1	1.06218	4946	7.117412	1.105493	1.640553

	I	J	K	L	M	N	O	P
1								
2								
3								
4								
5	mass flo	RHO C	RHO T	C STAR	TEMP K	condctvty	viscosity	heat cap
6	(relative)			feet/sec		(relative)	(relative)	
7								
8	1	0.001434	0.000889	5025.4	2933	52.16519	64.63423	44.9
9	0.983766	0.001434	0.000889	5025.4	2933	52.16519	64.63423	44.9
10	0.906639	0.001434	0.000889	5025.4	2933	52.16519	64.63423	44.9
11	0.62961	0.001434	0.000889	5025.4	2933	52.16519	64.63423	44.9
12	0.939366	0.002139	0.001324	5034.4	2957	52.39382	64.96114	45
13	1.24845	0.002841	0.001758	5039.1	2974	52.55518	65.18074	45
14	1.403434	0.003191	0.001976	5040.99	2980	52.61201	65.26385	45
15	1.558526	0.003541	0.002193	5042.85	2986	52.66878	65.34686	45
16								
17								
18								
19								
20								
21	RHO C	RHO T	C STAR					
22			feet/sec					
23								
24	0.001434	0.000889	5025.4					
25	0.001434	0.000889	5025.4					
26	0.001434	0.000889	5025.4					
27	0.001434	0.000889	5025.4					
28	0.001434	0.000889	5025.4					
29	0.002139	0.001324	5034.4					
30	0.002139	0.001324	5034.4					
31	0.002139	0.001324	5034.4					
32	0.002841	0.001758	5039.1					
33	0.002841	0.001758	5039.1					
34	0.003541	0.002193	5042.85					

	A	B	C	D	E	F	G	H
1								
2		TABLE 5. CHARACTERISTICS OF FIRST TEST PHASE MOTORS						
3								
4	MOTOR	Pressure	Burn time	throat dia	Grain I.D.	Gran lenth	H	Velocity
5		(psi	(sec)	(in	(in	(in	(relative)	(ft/sec)
6	steel 1	200	15	0.145	0.605	2.18	0.96	14.9
7	steel 2	400	12	0.12	0.447	2.25	1.23	10.2
8	C-130 1	200	6	0.145	0.605	0.9	0.96	14.9
9	A-625 1	200	6	0.145	0.605	0.9	0.96	14.9
10	A-950 1	200	10	0.126	0.604	1.45	1	14.5

Attachment 1

Procedure

VECTRA A950 CASE PREPARATON PROC

MATERIALS

10 VECTRA A950 CASES (NUMBERS 31-40)
POWER DRILL
WIRE BRUSH
ACETONE
R-45M
DDI
DBTDL
SMALL PAINT BRUSH
PLASTIC CUP

PROCEDURE

1) ROUGHEN THE INSIDE SURFACE OF THE CASES USING A POWER DRILL AND WIRE BRUSH.

2) WASH THE INSIDE SURFACES WITH A COAT OF ACETONE.

3) DRY OFF THE ACETONE WITH NITROGEN.

4) ADD 82.85 GRAMS OF R-45M TO THE PLASTIC CUP.

5) ADD 17.14 GRAMS OF DDI.

6) ADD 1 DROP OF DBTDL.

7) MIX.

8) USE A SMALL PAINT BRUSH TO COAT A LAYER (ABOUT 1/16 IN. THICK) OF THE R-45M/DDI ON THE INSIDE SURFACE OF THE CASES.

9) CAST THE PROPELLANT INTO THE CASES.

.84#/motor = 5000gm ≈ 12 motors + 500 gm extra   mayo copy

SOLID PROPELLANT PROCESSING SHEET

TITLE: RS-5	ENGINEER: NGUYEN	OPERATOR:	
BATCH NO:	MIXER: 1 GAL	BATCH SIZE: 5000	DATE:

ENGINEER'S COMMENTS:

MATERIAL	AMOUNT		WEIGHT			NOTES
R-45M	9.51 %	475.50 GR	N	T	G	905175
DOZ	2.00 %	100.00 GR	N	T	G	
TEPANOL	0.15 %	7.50 GR	N	T	G	HX-878
AO2246	0.100 %	5.00 GR	N	T	G	
AI (6 mc)	3.00 %	150.00 GR	N	T	G	KDX-65
AP (400 mc)	30.00 %	1500.00 GR	N	T	G	73047
AP (200 mc)	30.00 %	1500.00 GR	N	T	G	7781D
AP (50 mc)	10.00 %	500.00 GR	N	T	G	55-1-77
AP (10 mc)	13.00 %	650.00 GR	N	T	G	5325
DDI	2.24 %	112.00 GR	N	T	G	
	%	0.00 GR	N	T	G	
	.00 %	0.00 GR	N	T	G	
	%	0.00 GR	N	T	G	
	%	0.00 GR	N	T	G	
	%	0.00 GR	N	T	G	

PROCESSING STEP	RPM/SPEED	MINUTES	VACUUM	TEMP (DEG F)	INSTRUCTIONS
1 ADD FIRST INGREDIENTS	1	10	NO VAC	140 DEG F	R-45M/DOZ/TEPANOL/AO2246/AI
2 ADD 400mc & 50% 200mc AP	1	2/10	NO VAC/VAC	140 DEG F	
3 ADD 50 mc AP	1	2/15	NO VAC/VAC	140 DEG F	
4 ADD 10 mc AP	1	2/15	NO VAC/VAC	140 DEG F	
5 ADD 25% 200 mc AP	1	2/20	NO VAC/VAC	140 DEG F	
6 ADD 25% 200 mc AP	1	2/20	NO VAC/VAC	140 DEG F	
7 ADD DDI	1	2/15	NO VAC/VAC	140 DEG F	
8 CAST			VAC	140 DEG F	
9				DEG F	
10				DEG F	
11				DEG F	
12				DEG F	

TOTAL MIX TIME WILL BE 1 HOUR AND 57 MINUTES.

SOLVENT: CYCLOHEXANONE | COMMENTS: CLASS 1.3

MIXER'S COMMENTS:

MOLD: 2 HP 2X4'S / 10 PLASTIC 2X4'S | CURE OVEN: IN OUT

APC 2X4 EXPERMENTAL TEST FIRING PROCEDURE

1. LABEL TWO STEEL CASES, 1 THIN WALLED VECTRA A625 MOTOR AND 1 THIN WALLED VECTRA C130 MOTOR AND TEN THICK WALLED VECTRA A 950 MOTOR CASES

2. ROUGHEN THE TEN THICK WALLED CASES WITH A POWER DRILL STEEL BRUSH

3. BLOW OUT THE DEBRIS WITH NITROGEN

4. WASH THE INSIDE SURFACE WITH ACETONE

5. DRY WITH NITROGEN

6. WASH THE INSIDE SURFACE WITH METHANOL

7. MEASURE THE INSIDE DIAMETER 1/16", 1/2", AND 5/4" FROM THE NOZZLE END (THE THICK WALLED END IS THE NOZZLE END)

8. MEASURE THE OUTSIDE DIAMETER IN THE SAMES PLACES

9. MARK SPOTS FOR PLACING THERMOCOUPLES AS IN THE SKETCH IN FIGURE 6 AT:
   A. 2 MARKS 120 DEGREES APART 1/4" FROM THE NOZZLE END
   B. 2 MARKS 120 DEGREES APART 5/4" FROM THE NOZZLE END

11. IDENTIFY THERMOCOUPLE TYPE NEEDED FOR 150 TO 600 DECREES F RANGE

12. THIN THERMOCOUPLE BEAD JUNCTION

13. COVER THERMOCOUPLE JUNCTION WITH A SMALL BEAD OF EPOXY AND LET IT SET

14. CALIBRATE THERMOCOUPLES AT 0 DEG C, 40 DEG C, AND 100 DEG C, BY SOAKING THEM IN TEMPERATURE CONTROLLED WATRER

15. ESTIMATE THERMOCOUPLE LAG TIME BY QUENCHING IT FROM 0 DEG C ICE WATER TO 100 DEG C BOILING WATER AND PLOTTING CHAMGE OF TEMPERATURE READING WITH TIME

16 ATTACH THERMOCOUPLES AT PREMARKED SPOTS WITH EPOXY

17. WEIGH CASES

18. MACHINE THE GRAINS OF THE 2 STAINLESS STEEL MOTORS, THE TWO THIIN WALLED VECTRA CASES, AND ONE THICK WALLED VECTRA CASE PER TABLE 5 AND FIGURE 6.

19 PUT IN NOZZLES WITH THE DIAMETER IN 2X4 SKETCHES

20 PUT IN THERMALITE IGNITERS

21 PUT 2X4'S ON TEST STAND AND CONNECT THERMOCOUPLES AND PRESSURE TRANSDUCER TO INSTRUMENTAION WHICH CAN RECORD ALL READINGS VERSUS TIME

22 CHECK TEMPERATURE AND TRANSDUCER READINGS BEFORE FIRING

23 FIRE THE TWO STEEL CASE MOTERS AND ONE THICK WALLED VECTRA MOTOR WHILE MEASURING PRESSURE AND TEMPERATURE VERSUS TIME

24 WITH THREE PRONGED MICROMETER MEASURE THE CHARRED IINNER DIAMETER AT THE THERMOCOUPLE POINTS ON THE VECTRA CASE TO FIND THE AMOUNT OF ABLATION

25 WEIGH CASES

26 SCRAPE OUT THE CHAR LAYER AND MEASURE THE ID AGAIN TO FIND THE CHAR DEPTH

27 WEIGH CASES

28 CALCULATE THE CHAMBER GAS HEAT TRANSFER COEFFICIENT AND THERMAL GRADIANT IN EADH WALL

29 CALCULATE SAFELY SUSTAINABLE FIRING TIMES AND PRESSURES IN THICK WALLED VECTRA CASES

30 MACHINE THE GRAINS OF THE REMAINING NINE THICK WALLED VECTRA MOTORS PER THE INFORMATION GAINED IN STEPS 24 THRU 29

31 REPEAT STEPS 19 THRU 29

32 SECTION AND PHOTOMICROGRAPH

33 WRITE REPORT AND REVIEWED PAPER

Attachment 2

Previous Data

LCP END-BURNING 2X4 F

FIRING NUMBER	CASE MATERIAL	PRESSURE (PSI)	DURAT (SEC	
1	RYTON	196	11.	
2	VECTRA C130	>1100	4.0	OVERPRESSURED (INHIBITOR UNBONDED ?)
3	VECTRA A625	201	10.5	FAILED @ t= +10.5 SEC

LCP 2X4 FIRINGS

FIRING NUMBER	CASE MATERIAL	PEAK PRESSURE (PSI)	AVERAGE PRESSURE (PSI)	DURATION (SEC)	CASE/PROPELLANT BOND PROMOTER	COMME
1	VECTRA C130	961	864	1.446	N-100	
2	VECTRA C130	1278		.070	NONE	FAILED IGNITI
3	VECTRA C130	1018	990	1.376	NONE	
4	VECTRA C130	1303		.059	N-100	FAILED IGNITI
5	VECTRA A625	966		.058	N-100	FAILED IGNITI
6	VECTRA A625	1019		.807	N-100	FAILED @ +.80
7	VECTRA A625	862	818	1.436	NONE	
8	VECTRA A625	913	876	1.419	NONE	
9	RYTON	316	269	2.346	NONE	
10	RYTON	753	727	1.578	N-100	
11	RYTON	745	713	1.605	NONE	

DEVELOPMENT AND TESTING OF LIQUID CRYSTAL POLYMER SOLID ROCKET MOTORS

Tracy R. Reed
Student
Tehachapi High School

Final Report for:
Summer Research Program
Phillips Laboratory

Sponsored by:
Air Force Office of Scientific Research
Bolling Air Force Base, Washington, D.C.

August 1993

DEVELOPMENT AND TESTING OF LIQUID CRYSTAL POLYMER SOLID ROCKET MOTORS

Tracy R. Reed

Abstract

A working solid rocket motor with all structural components made out of liquid crystal polymers (LCP's) was built and tested. The motor cases and nozzles were injection molded. Three propellant formulations with different burn rates were tested in the motors. After development and testing, the rocket motors will be sent to the U.S. Air Force Academy for their advanced Astronautics curricula.

DEVELOPMENT AND TESTING OF LIQUID CRYSTAL POLYMER SOLID ROCKET MOTORS

Introduction

The goal of this experiment was to develop and produce a working solid rocket motor with nozzle and case made out of Liquid Crystal Polymers (LCP's). Three different propellants with three different burn rates were formulated. Due to the nature of LCP's, it was necessary that the propellants be non-aluminized to cut down on nozzle throat erosion. After development and testing, the motors were sent to the U.S. Air Force Academy for ground launch. These newly developed motors will replace the old motor the Academy used in its experiments. The rocket motor used at the Academy is often referred to as the Academy motor. The old Academy motor was labor intensive and expensive to produce. The new motor requires very little machining and is easy to assemble. The cases and nozzles are injection molded into the correct shape. This cuts down on the cost of machining the case and nozzle, as was required by the old Academy motor. The old Academy motor used only one propellant formulation. Three new propellants were developed for the new motor to provide more flexibility.

Procedure

The first step in the development of the motor was the propellant formulation. Three different types of propellant were developed with three significantly different burn rates. The propellant was based on the prior Academy motor propellant and

modified to produce the new propellants. Each propellant was to have a unique plume and physical color. Different additives were added to each propellant to provide these different colors. The physical color of the propellant was easy to achieve due to the different colors of the burn rate modifiers. The unique plume colors were significantly more difficult. The propellants were referred to as high, medium, and low, according to burn rate. The high propellant is black, the medium propellant is red, and the low propellant is yellow. The plume color for the high propellant is green, medium is red, and low is blue. The theoretical I_{sp} for all of the propellants is approximately 240 sec. to give all of the motors the same total impulse.

All solid ingredients were dried in a drying oven for at least 24 hours before being used except for the copper ammonium chloride which was ground and dried until all water appeared to be driven from the hydrated crystals. This turns the blue crystals into a red-brown powder. To date, only the medium propellant has been successfully mixed and fired in an Academy motor. The low propellant began to cure in the mixing pot on attempts to mix it. This may be happening due to the copper ammonium chloride which may be acting as a cure catalyst causing the propellant to cure faster than it should. Great effort was required to get the low propellant cast before it was completely cured in the pot. This propellant was hand cast into the 2x4 motors due to its extreme viscosity. The other two propellants were vacuum cast. All of the propellants have been fired in a 2x4 motor configuration to provide burn rate and K_n data. The high propellant has not been cast into Academy motors yet, but this should occur in the near future. More effort will have to be put into the low propellant cure problem.

The propellants were cast into cardboard tubes for the Academy motor that had been lined on the inside with a mixture of R45M (a hydroxy terminated polybutadiene) containing AO2246 (an anti-oxidant) and DDI (dimeryl diisocyanate) to ensure a good bond between the propellant and the tube. This tube was then fit into an outer tube. The

two tubes fit perfectly inside one another. The outer tube was then cut to 7 1/4" long. The inner tube containing the propellant was slid into the outer tube, and this whole assembly was inserted into the motor. The nozzle was then pressed into place and held with rivets. Detailed instructions on the assembly of an Academy motor may be found near the end of this paper.

The original grain design was a grain 7 1/4" long with a 3/8" bore. The propellant was then to be cut radially into three pieces. The first was to be 2 1/2" long, the second 2", and the third 2 1/2". This would allow the propellant to burn in the center as well as on the ends. This was to provide even surface area throughout the burn. The combustion chamber in the case is slighly larger than 7 1/4" long. This allowed the propellant grains to move around slightly. It was discovered during the first five test firings that there was a tremendous pressure differential over the length of the propellant grain. This caused the propellant segment nearest the nozzle of the motor to be forced down the nozzle intake, compressing the end of the propellant and pinching off the flow of exhaust. This caused an immediate over-pressurization and explosion of the case. The solution to the problem was a phenolic spacer between the nozzle and propellant that would hold the propellant firmly in place. Cardboard spacers made out of the same material as the inner tube were first tried, but it was found that they lacked sufficient compressive strength. During the subsequent firings of the Academy motors the LCP nozzle throat eroded to such an extent that the pressure loss inside the motor became unacceptable. It was decided that the burn time must be made short enough such that all of the propellant could be burned before the nozzle eroded completely through. Various grain configurations were tried in an effort to increase the burn surface area. The final solution was to inrease the bore to 49/64" with no radial cuts. This worked quite well, giving a burn time of approximately 3 seconds with a maximum thrustof approximately 50 lbs. All motor testing was done on pad 44 in area 1-30 at Phillips Laboratory, Edwards Air Force Base. Burn rate and K_n dat may be

found at the end of this paper. K_n is defined as A_{grain}/A_{throat}. Burn rate is in in./sec.

Results

It was proven that an all LCP rocket motor could be manufactured and fired. Three propellants with different burn rates were formulated and tested by means of 2x4 and LCP motor firings. An all LCP case and nozzle was engineered, tested, and found capable of withstanding the required operating pressures. The nozzle still erodes significantly, just barely burning though the nozzle throat. In the future, nozzles may be coated with silicon nitride or silicon carbide in an attempt to relieve this problem. This should give a significant increase in motor performance.

ACADEMY MOTOR PROPELLANT FORMULATIONS

High

Ingredient	% by weight
R45M with AO2246	10.46
DOZ	2.15
DDI	2.39
AP (400 mc)	27.11
AP (200 mc)	27.11
AP (25 mc)	20.78
Boron	5.00

Medium

Ingredient	% by weight
R45M with AO2246	10.46
DOZ	2.15
DDI	2.39
AP (400 mc)	25.17
AP (200 mc)	25.17
AP (25 mc)	25.17
Fe_2O_3	0.20
$Sr(NO_3)_2$	9.29

Low

Ingredient	% by weight
R45M with AO2246	10.46
DOZ	2.15
DDI	2.39
AP (400 mc)	40.00
AP (200 mc)	20.00
AN	15.00
Copper ammonium chloride	2.00
Potassium perchlorate	8.00

INSTRUCTIONS FOR ASSEMBLING AN ACADEMY MOTOR

1. Bore nozzle to 54/64" using a type Q drill.

2. Cut outer tube to 7 3/4" long.

3. Insert out tube into case and compress.

4. Tape 1" long phenolic spacer to the end of the propellant grain using 1 layer of masking tape.

5. Slide grain into outer tube in case and press down firmly.

6. Trial fit nozzle on the end of the motor making sure that there is no more than a 1/8" gap between the nozzle and the end of the case.

7. Prepare polyurethane sealant.

8. Apply polyurethane to the nozzle end of the motor case and both sealing surfaces on the nozzle.

9. Wipe off excess polyurethane.

10. Insert nozzle and compress.

11. Insert 2 1/8" rivets each on opposites sides of the motor and use a vice to press them in. Rivets should go in firmly, but don't force them. Make sure the holes on the nozzle and case are aligned.

12. Insert other 2 rivets using the same procedure as step 11.

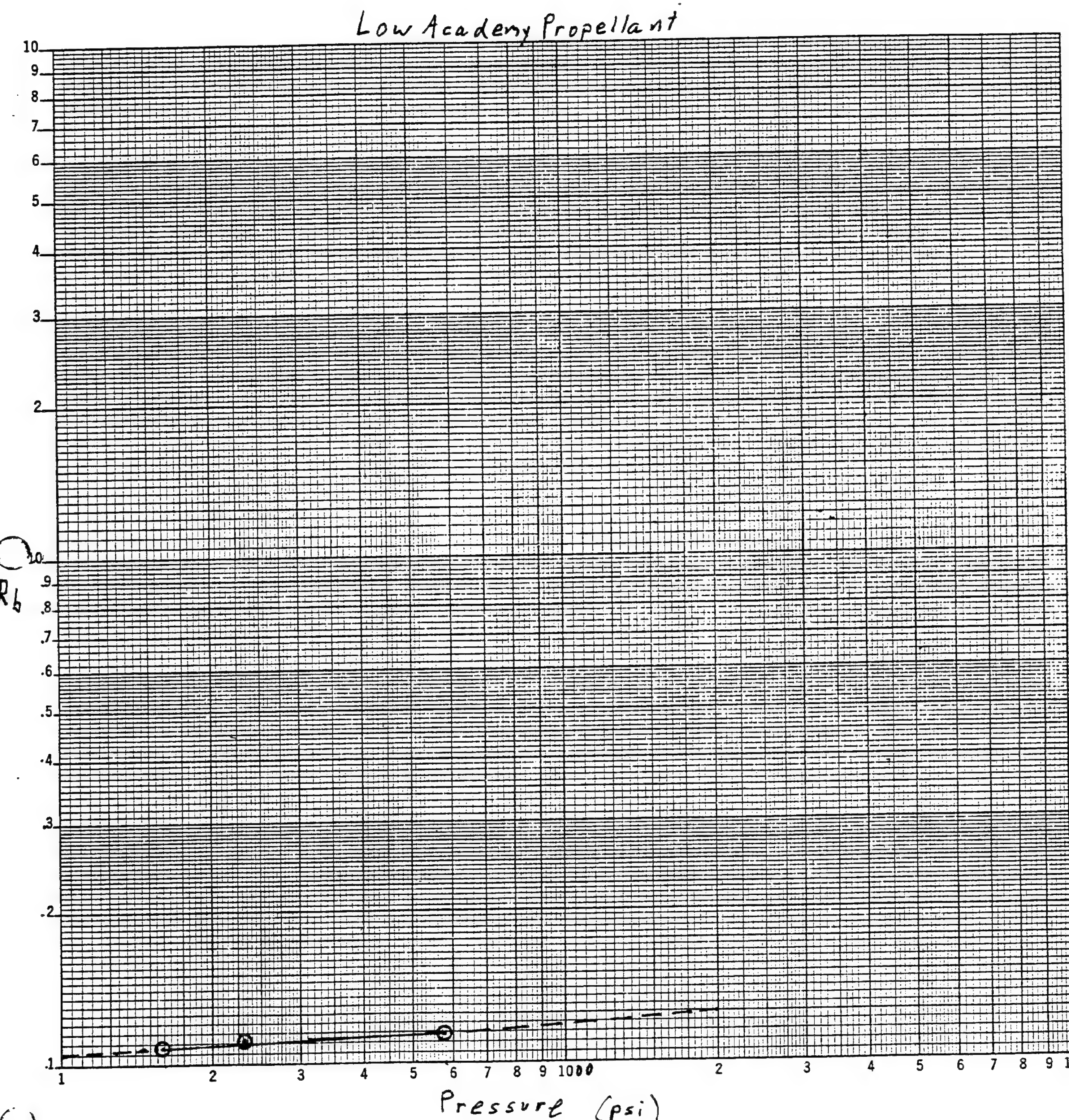
13. Prepare the igniter by cutting a piece of the ANB to 1/4x1/4x1/8".

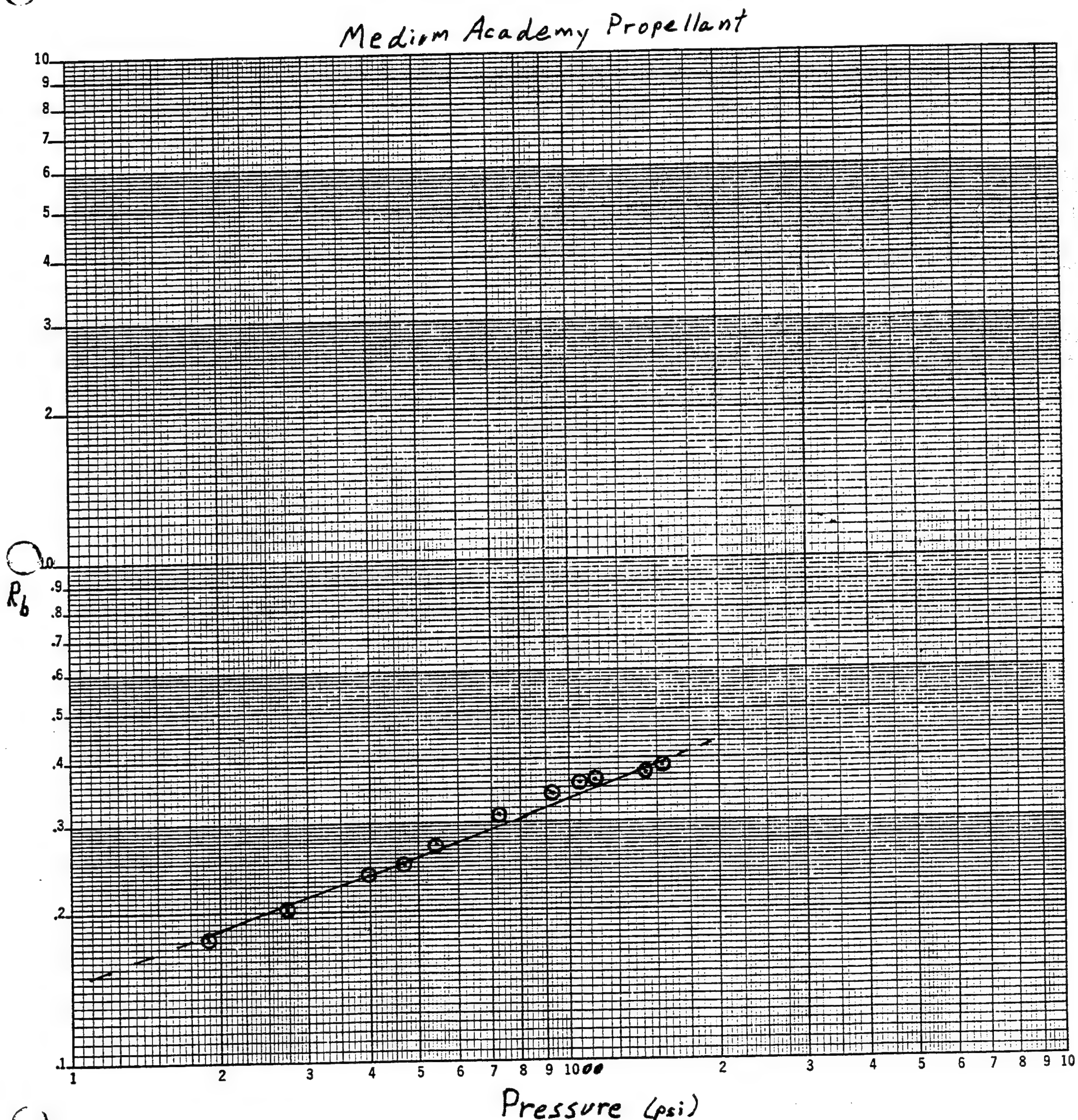
14. Push 4" of #26 nichrome wire through the center of the face of the propellant.

15. Cut 18" of #26 strain gauge wire (stranded) and twist 1 1/2" of it to the nichrome wire.

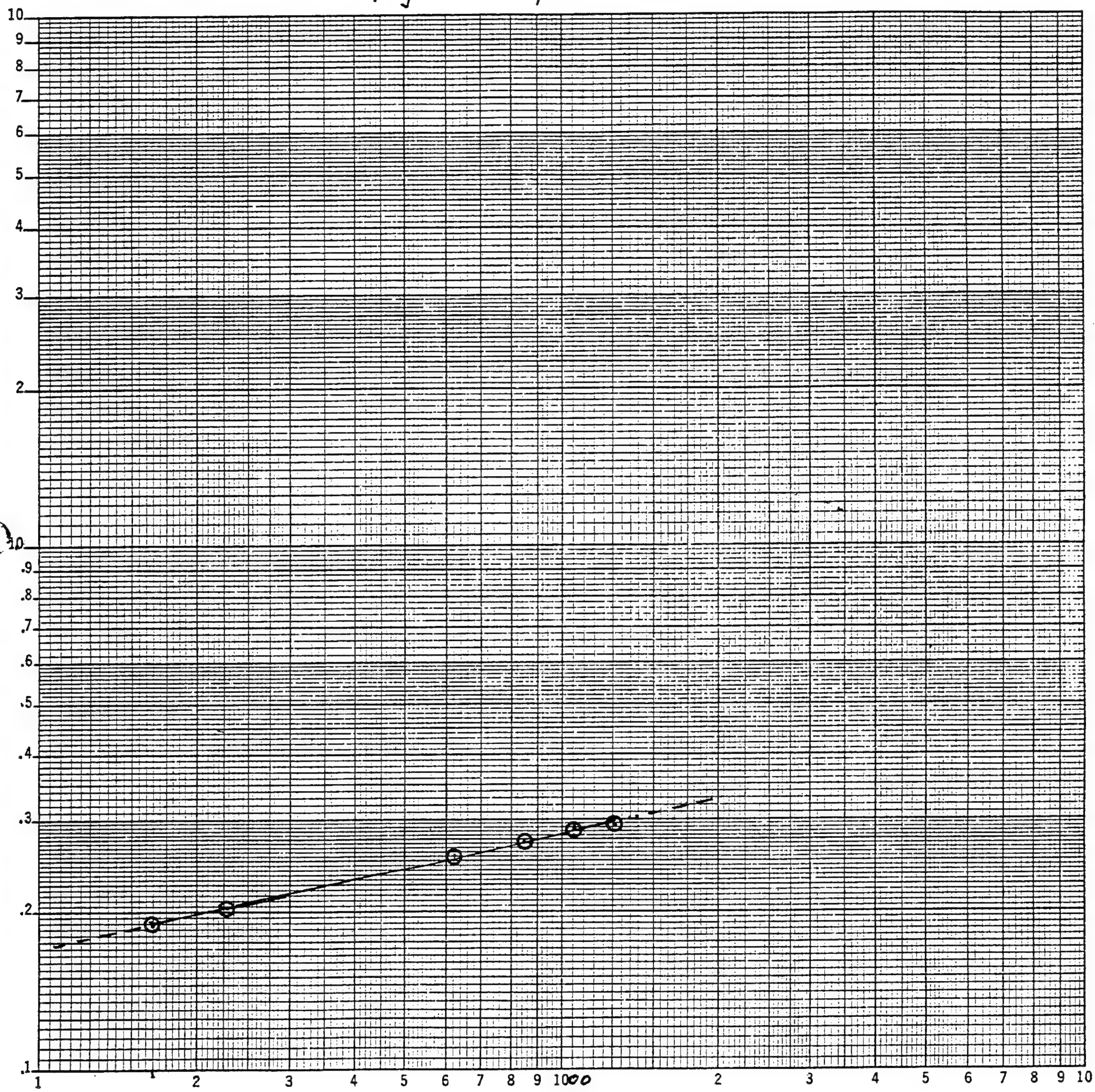
16. Insert the igniter 1/2 way down propellant grain.

17. Secure the igniter wires to bottom of motor with tape.

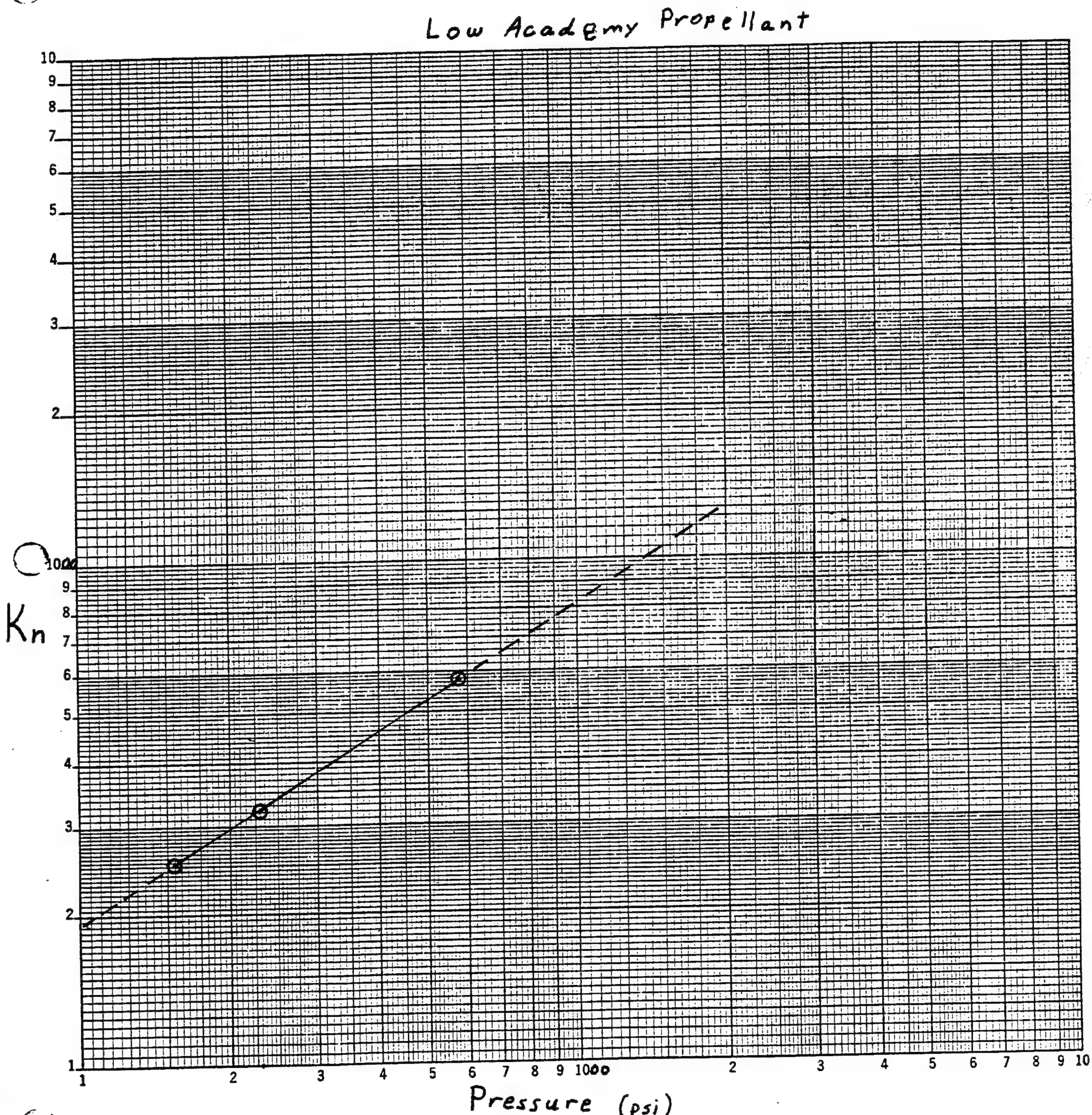

Low Academy Propellant
10
9
8
7
6
5
4
3
2
10
Rb
.9
.8
.7
.6
.5
.4
.3
.2
.1
1
2
3
4
5
6
7
8
9
1000
2
3
4
5
6
7
8
9
10
Pressure (psi)

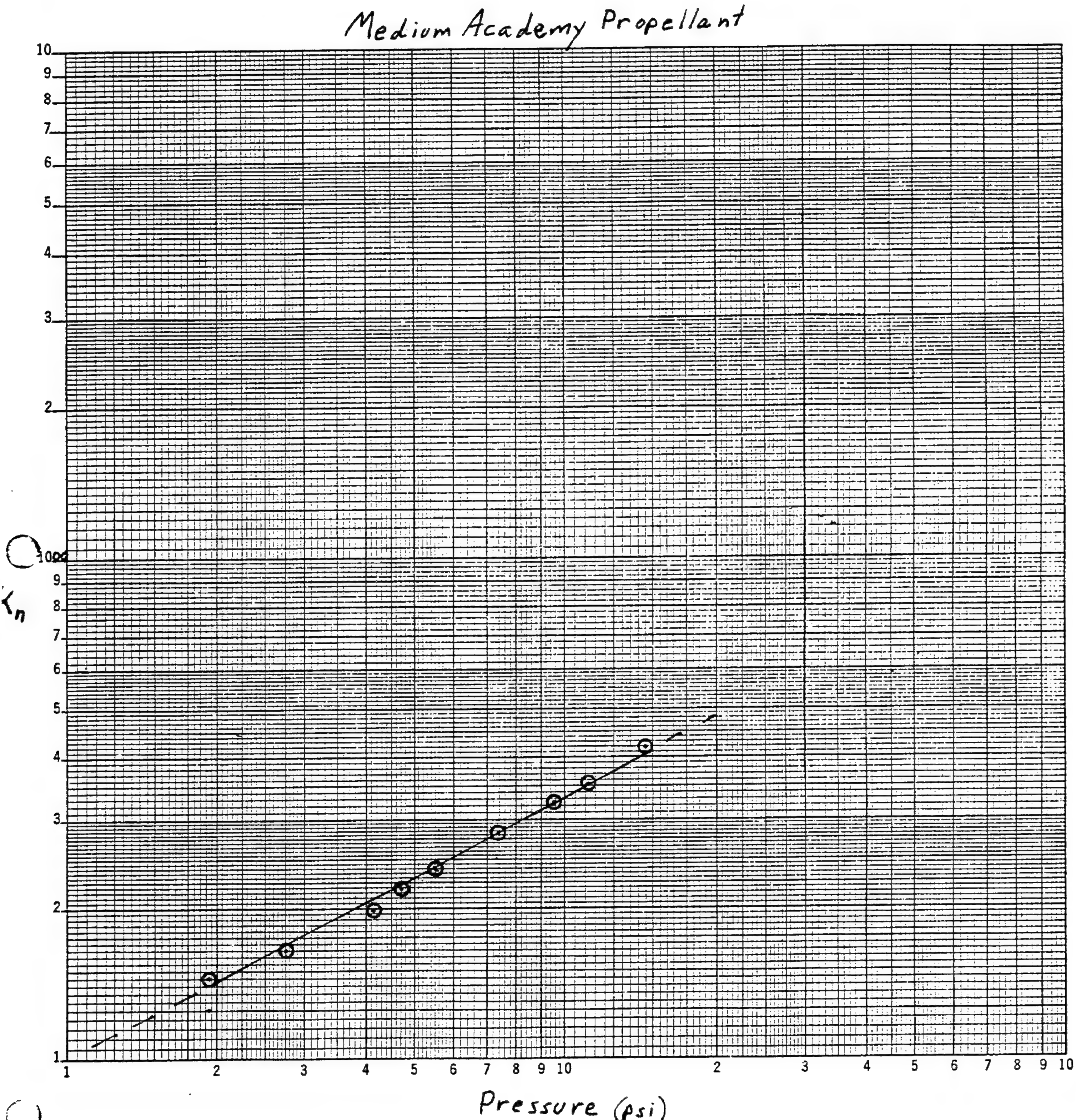

Medium Academy Propellant
R_b
Pressure (psi)
10
9
8
7
6
5
4
3
2
.10
.9
.8
.7
.6
.5
.4
.3
.2
.1
1
2
3
4
5
6
7
8
9
1000
2
3
4
5
6
7
8
9
10

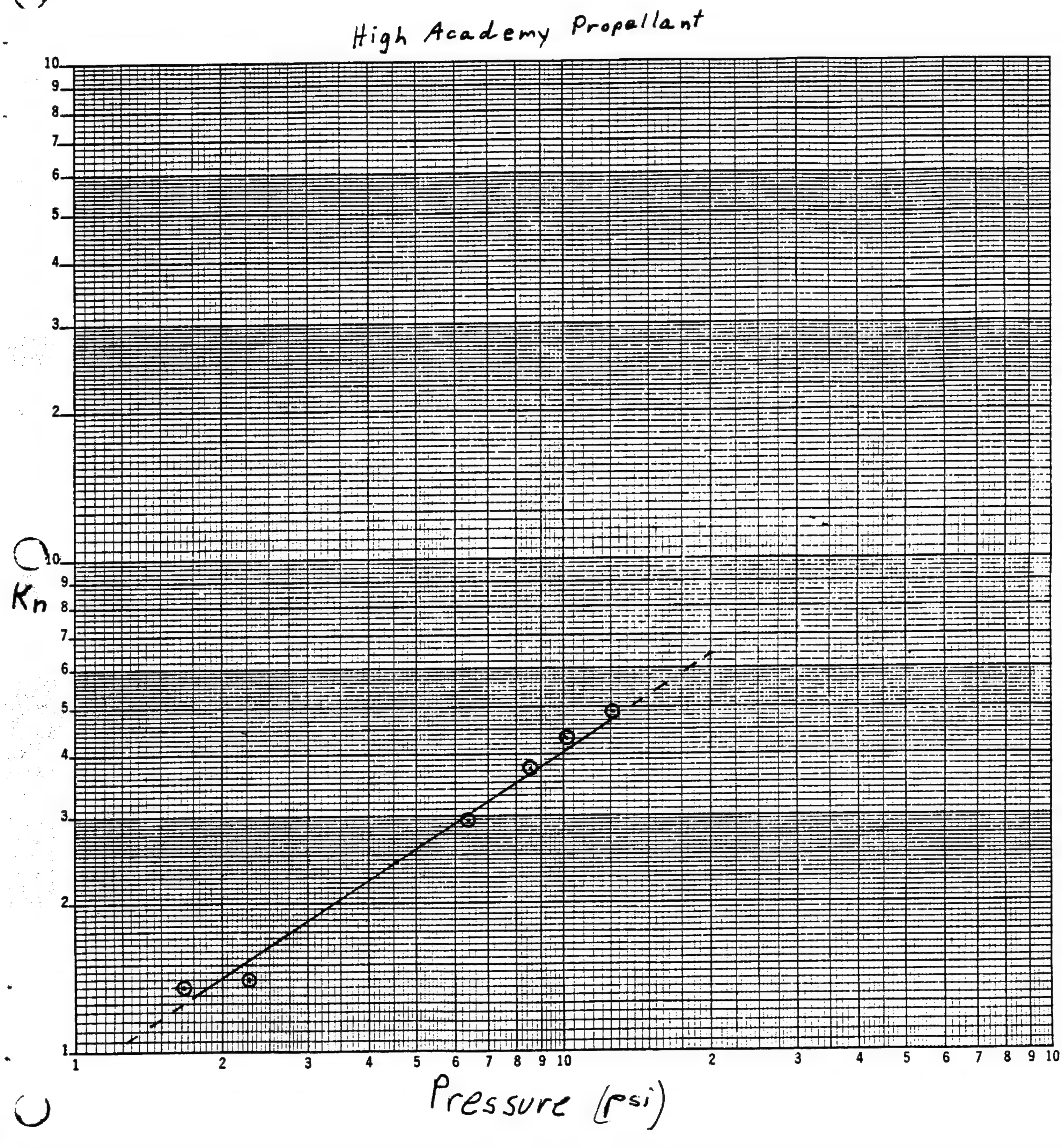
High Academy Propellant



Pressure (psi)


Low Academy Propellant
Kn
Pressure (psi)
10
9
8
7
6
5
4
3
2
1000
1
1
2
3
4
5
6
7
8
9
1000
10


Medium Academy Propellant
10
9
8
7
6
5
4
3
2
1000
9
8
7
6
5
4
3
2
1
r_n
1
2
3
4
5
6
7
8
9
10
2
3
4
5
6
7
8
9
10
Pressure (psi)


High Academy Propellant
Kn
Pressure (psi)

The ASTRONAUTICS LABORATORY Theoretical ISP Program
Micro Version by Beckman & Acree Revision: 5/89 13:10:36 21-

PROPELLANT	HF	DENSITY	WEIGHT	MOLES	VOLUME
AP	-70.6900	1.9500	60.0000	.5107	30.7692
R-45	-.2500	.9300	10.4600	.1675	11.2473
DOZ	-336.8000	.5190	2.1500	.0052	4.1426
DDI	-206.3000	.9240	2.3900	.0041	2.5866
AN	-87.2000	1.7300	15.0000	.1874	8.6705
CuAMCl	-70.0000	2.0000	2.0000	.0072	1.0000
KClO4	-102.8000	1.7300	8.0000	.0577	4.6243

GRAM ATOMS / 100 GRAMS
C .9559 CL .5973 CU .0072 H 4.4129 K .0577 N .9081 O 2.9664

ENTHALPY = -61.52411 DENSITY =1.586
CSTAR (FT/SEC)= 4844.128

	CHAMBER	THR(SHIFT)	EXH(SHIFT)
PRESSURE (PSIA)	1000.00	566.036	14.6960
EPSILON	.000000	1.00000	8.49201
ISP	.000000	101.717	238.594
ISP (VACUUM)	.000000	186.942	257.384
TEMPERATURE(K)	2773.08	2534.26	1317.30
MOLECULAR WEIGHT	25.2081	25.2751	25.4036
MOLES GAS/100G	3.96698	3.95646	3.93645
CF	.000000	.675590	1.58470
PEAE/M (SECONDS)	.000000	85.2246	18.7902
GAMMA	1.21713	1.21954	1.25215
HEAT CAP (CAL)	44.1909	43.6755	38.8467
ENTROPY (CAL)	239.204	239.203	239.204
ENTHALPY (KCAL)	-61.5241	-73.4098	-126.921
DENSITY (G/CC)	.75381E-02	.46813E-02	.23501E-03
ITERATIONS	23	14	25

PROPELLANT	HF	DENSITY	WEIGHT	MOLES	VOLUME
AP	-70.7000	1.9500	74.8000	.6367	38.3590
R-45	-.2500	.9300	10.4600	.1675	11.2473
DOZ	-336.8000	.5190	2.1500	.0052	4.1426
DDI	-206.3000	.9240	2.3900	.0041	2.5866
FE2O3	-197.0000	5.1200	.2000	.0013	.0391
SR(NO3)2	-233.8000	2.9860	10.0000	.0473	3.3490

GRAM ATOMS / 100 GRAMS
C .9559 CL .6367 FE .0025 H 4.0807 N .7394 O 2.9500 SR .0473

ENTHALPY = -58.94820 DENSITY =1.674
CSTAR (FT/SEC)= 4863.014

	CHAMBER	THR(SHIFT)	EXH(SHIFT)	EXH(SHIFT)
PRESSURE (PSIA)	1213.00	691.096	14.6900	4.75867
EPSILON	.000000	1.00000	10.2562	23.9999
ISP	.000000	101.174	244.861	263.319
ISP (VACUUM)	.000000	187.291	263.636	277.551
TEMPERATURE(K)	2944.47	2719.11	1460.60	1190.93
MOLECULAR WEIGHT	26.8584	26.9818	27.4697	27.4763
MOLES GAS/100G	3.72323	3.70621	3.64037	3.63950
CF	.000000	.669373	1.62002	1.74214
PEAE/M (SECONDS)	.000000	86.1170	18.7740	14.2313
GAMMA	1.21125	1.21252	1.23237	1.24428
HEAT CAP (CAL)	42.4241	42.0213	38.3670	36.8405
ENTROPY (CAL)	228.773	228.772	228.773	228.773
ENTHALPY (KCAL)	-58.9478	-70.7069	-127.825	-138.601
DENSITY (G/CC)	.91753E-02	.56868E-02	.22910E-03	.91042E-04
ITERATIONS	9	20	48	33

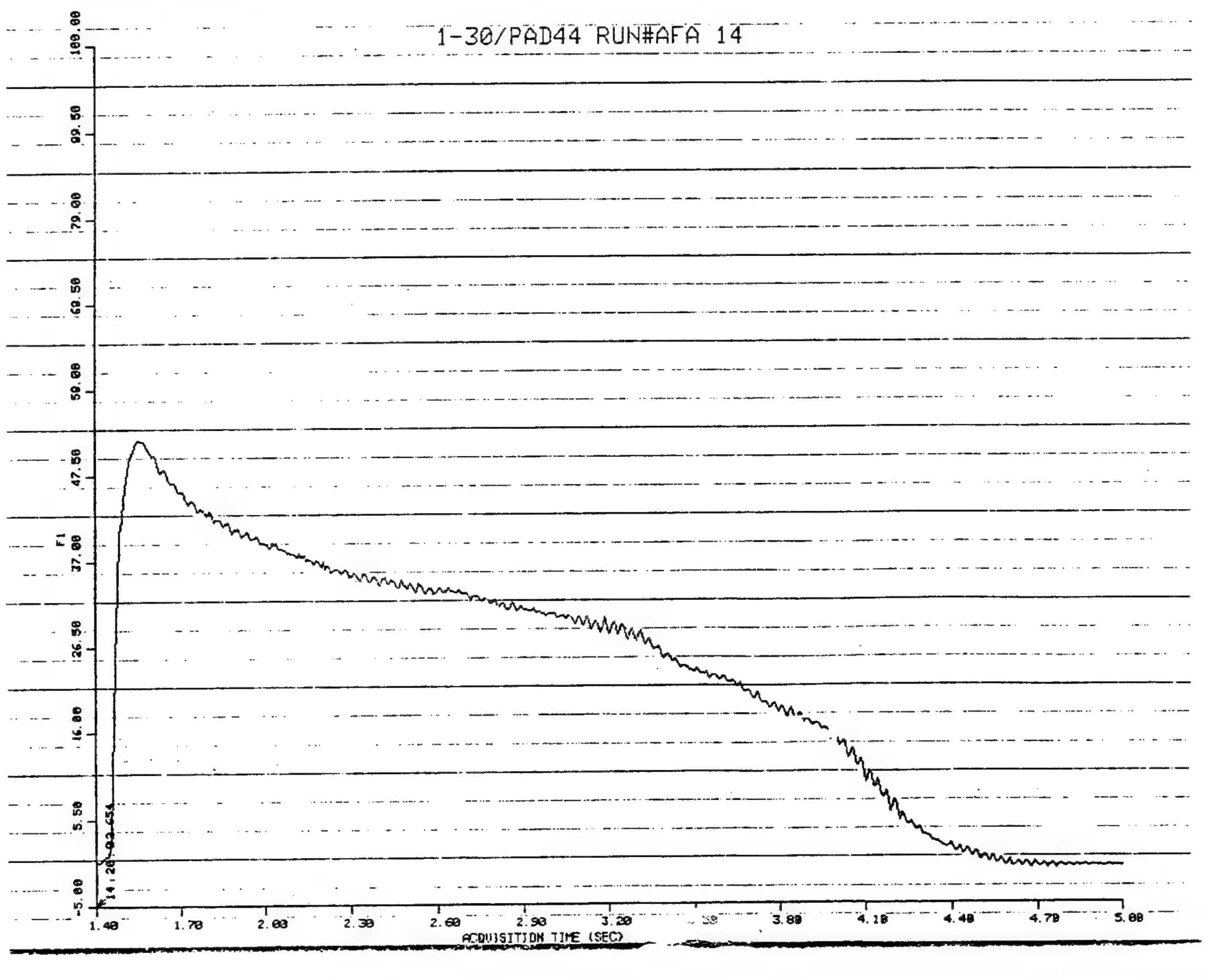
The ASTRONAUTICS LABORATORY Theoretical ISP Program
Micro Version by Beckman & Acree Revision: 5/89 13:11:02

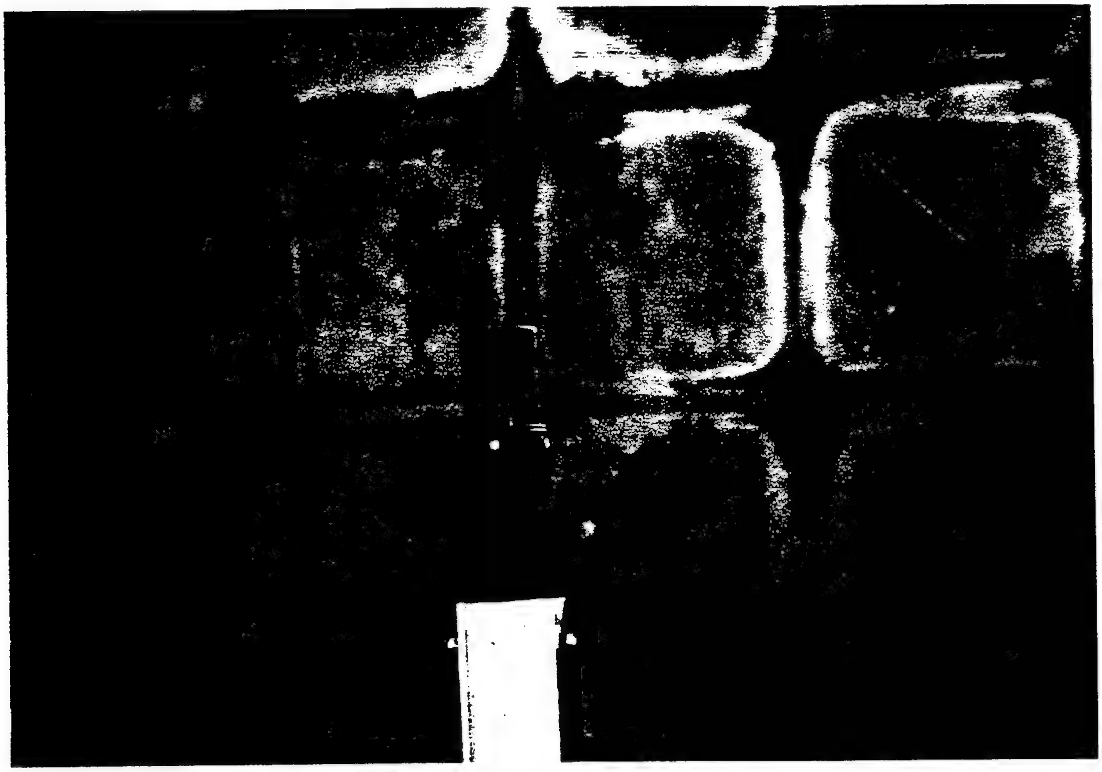
PROPELLANT	HF	DENSITY	WEIGHT	MOLES	VOLUME
AP	-70.6900	1.9500	75.0000	.6384	38.4615
R-45	-.2500	.9300	13.9500	.2233	15.0000
DOZ	-336.8000	.5190	2.8600	.0069	5.5106
DDI	-206.3000	.9240	3.1900	.0055	3.4524
BORON	.0000	2.3400	5.0000	.4625	2.1368

GRAM ATOMS / 100 GRAMS
B .4625 C 1.2745 CL .6384 H 4.5988 N .6493 O 2.7082

ENTHALPY = -48.64441 DENSITY =1.549
CSTAR (FT/SEC)= 4824.350

	CHAMBER	THR(SHIFT)	EXH(SHIFT)
PRESSURE (PSIA)	1000.00	560.671	14.6960
EPSILON	.000000	1.00000	9.44873
ISP	.000000	102.675	244.742
ISP (VACUUM)	.000000	186.748	265.564
TEMPERATURE(K)	2492.92	2246.21	1395.80
MOLECULAR WEIGHT	22.4660	22.4973	23.6810
MOLES GAS/100G	4.45117	4.44497	4.22280
CF	.000000	.684751	1.63220
PEAE/M (SECONDS)	.000000	84.0722	20.8217
GAMMA	1.24040	1.24406	1.23906
HEAT CAP (CAL)	45.6406	45.0262	43.4950
ENTROPY (CAL)	251.367	251.367	251.367
ENTHALPY (KCAL)	-48.6444	-60.7551	-117.455
DENSITY (G/CC)	.74731E-02	.46567E-02	.20676E-03
ITERATIONS	25	7	21





Academy motor on pad 44 after firing.

Acknowledgments

I wish to thank Mr. Hieu Nguyen who was a great help throughout the course of this project. I also wish to thank Dr. John Rusek and Dr. Kevin Chaffee for all of their advice and help. Finally, I wish to thank the crew of Area 1-30 for their constant cooperation and understanding.

DEVELOPMENT AND TESTING OF LIQUID CRYSTAL POLYMER SOLID ROCKET MOTORS AND HYDROSTATIC TESTING OF LIQUID CRYSTAL POLYMER ROCKET MOTOR CASES

Tracy R. Reed

San Diego State University

Final Report for:

Summer Research Program

Phillips Laboratory

August 1994

DEVELOPMENT AND TESTING OF LIQUID CRYSTAL POLYMER SOLID ROCKET MOTORS AND HYDROSTATIC TESTING OF LIQUID CRYSTAL POLYMER ROCKET MOTOR CASES

Tracy R. Reed

Abstract

A solid rocket motor with nozzle and case made out of liquid crystal polymers (LCP's) was built and tested. This work was a continuation of the work done in the summer of 1993. The rocket motor cases and nozzles were injection molded. In addition, hydrostatic testing of liquid crystal polymer 2x4's was performed to determine their burst pressure and tensile strength, whichare directly related to the properties of the rocket motor cases. Molecular models of LCP's were also drawn.

DEVELOPMENT AND TESTING OF LIQUID CRYSTAL POLYMER SOLID ROCKET MOTORS AND HYDROSTATIC TESTING OF LIQUID CRYSTAL POLYMER ROCKET MOTOR CASES

The goal of this project is to produce a working solid rocket motor with the nozzle and case made out of liquid crystal polymers (LCP's). This work is a continuation of work done during the summer of 1993. Once operational, these motors will be delivered to the Air Force Academy for use in their curriculum. There were three main parts to the summers activities: molecular modeling, hydrostatic testing of LCP 2x4's, and Academy motor development.

Molecular models showing the structure of 7 liquid crystal polymers were drawn. Various molecular modeling programs were tried, but only Autocad produced the kind of drawings that were desired. Two dimensional drawings depicting the hydroquinone terepthalic acid backbone and the pedant groups were the result of this effort. The LCP's drawn are: phenyl ethyl hydroquinone terepthalic acid, chloro hydroquinone terepthalic acid, hydroquinone terepthalic acid, bromo hydroquinone terepthalic acid, phenyl hydroquinone terepthalic acid, tertiary butyl hydroquinone terepthalic acid, methyl hydroquinone terepthalic acid.

The hydrostatic testing of the LCP rocket motor cases was done on pad 44 of area 1-30 at Phillips Laboratory, Edwards AFB. The hydrostatic test equipment was provided

by area 1-32. Materials tested were Vectra B950, A950, B420, B230, and HX-4000. The cases were filled with water and then pressurized with nitrogen until they burst. Burst pressures were recorded. The motors were molded with a slight taper on the inside. Some of the motors were machined such that the taper was removed. These motors are denoted with an M after the test article number, which is in the leftmost column in the 2x4 burst test data. All machined motors were placed in the test fixture thin side down for consistency. The A950 machined specimens had a noticeable impurity inclusion (presumably from a previous material run through the injection molder). It was anticipated that the cases would fail along this inclusion. All of the machined A950 tested did indeed fail along the inclusion. This shows that purity is very important to having a high burst strength, and a high tensile strength. Tensile strength values along the direction of molecular orientation were available from the manufacturer of the polymer for some of the LCP's that were tested. A comparison of the predicted burst pressures and the actual burst pressures shows the actual tensile strength of the material in the test articles:

Material	Tensile Strength (psi)	Pred.Burst Pressure(psi)	Actual Burst Pressure (psi)	Actual Tensile strength(psi)
B230	35000	3889	1260	11340
B420	17000	1889	507	4563

The tensile strength of B230 is 32.4% of what the manufacturer found it to be. The tensile strength of B420 is 26.8% what the manufacturer found it to be. This suggests that our processing technique is not optimal. The injection molding process does not orient the polymer in the hoop direction, which is preferred for rocket motor cases. Photos were taken

of every motor tested to make a permanent record of how the case failed and what the fracture surface looks like.

The cases for the Academy motor were injection molded at Hill AFB and tested on pad 44 in area 1-30 at Phillips Laboratory, Edwards AFB. The propellant used was slightly modified from that of last summer. The additives for plume color complicated the mix process and it was decided to leave them out. The new propellant formulation can be found on the solid propellant processing sheet included in this paper. The included processing sheet is for the medium burn rate propellant. For the high burn rate propellant, .2% iron oxide was substituted for the .2% carbon black. This propellant has very good processing characteristics and cures in 24 hours. Propellant is cast directly into the motor cases. The propellant was mixed in a 1 gallon mixer in the new mix facility in area 1-30.

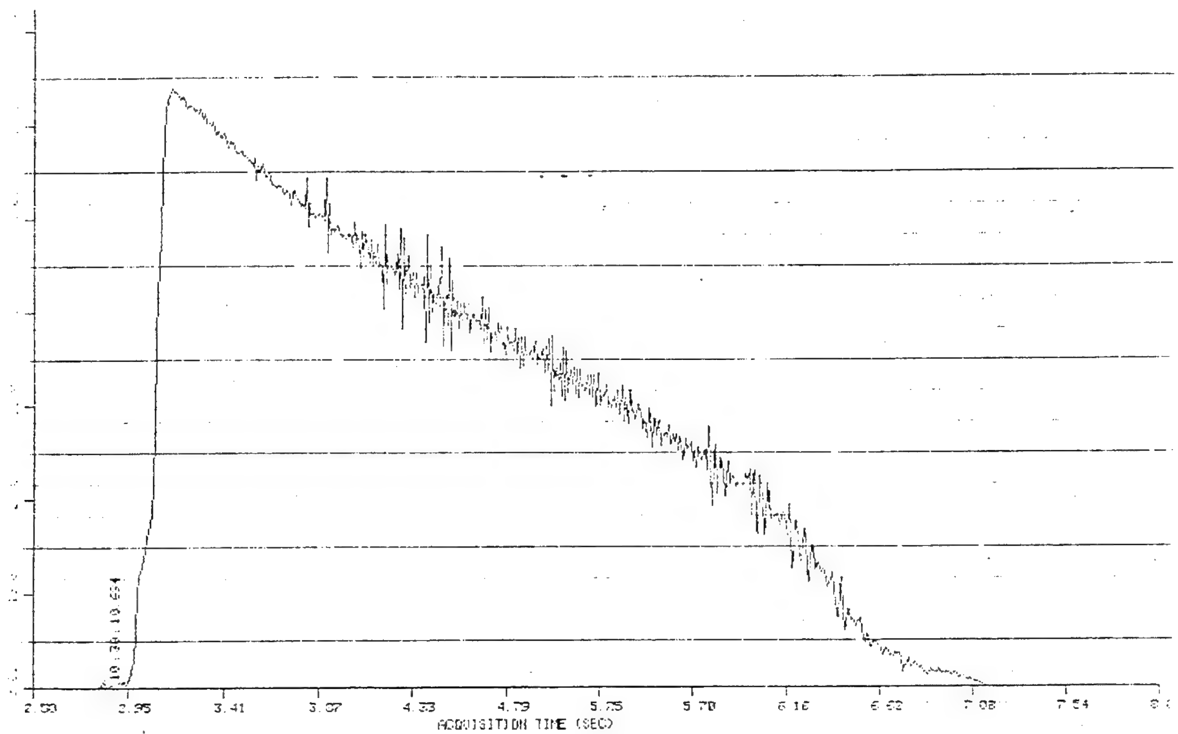
One successful firing was conducted which resulted in a peak thrust of 63 pounds, an action time of approximately 3 seconds, and a total impulse of 129 pound-seconds. The nozzle throat diameter was bored to .3281 inches which should result in a case pressure of 500 psi.. Numerous other firings at higher pressures resulted in blown nozzles. Higher pressures are desired (on the order of 1000 psi) to increase motor performance.

The current motor design calls for the nozzle to be held in place by 4 rivets, .125" in diameter. Great care must be taken to put the rivets in without cracking the boss on the nozzle or splitting the case. The nozzles were not perfectly round and had to be machined to fit into the case. Upon firing, the rivets would pull through the case and the nozzle would blow off. This is believed to be because of the high anisotropy of the rocket motor case, this was not taken into account in the design of the motor. The hydrostatic testing of the 2x4 motor cases also suggested high anisotropy. There are several things that may

solve this problem. The first would be to blow mold the case. This would orient the polymers in the direction of the hoop stress, which is the optimal situation. Another improvement would be to use another way of holding the nozzle in the case. One idea is to make a capture which will go over the nozzle and thread onto the case, locking the nozzle in place. If the case were blow molded and the capture was injection molded, the orientation in both parts would provide maximum strength in the desired directions.

The molecular models will help to visualize the polymer backbone and the pendant group to aid in the study of the interactions between the polymer molecules. The hydrostatic testing of the 2x4 motors has shown the kind of burst pressures that can be expected with these polymers and current processing methods. Several fundamental design problems were recognized and solutions proposed to solve them. Once these solutions are implemented, it is believed that a liquid crystal rocket motor with good performance characteristics will finally be realized.

Time vs. pressure plot of a successful motor firing, The action time was 3 seconds, pressure was 500 psi, peak thrust was 63 pounds.

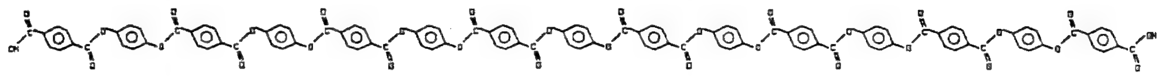


Hydrostatic testing data. All designations ending with M are machined cases.

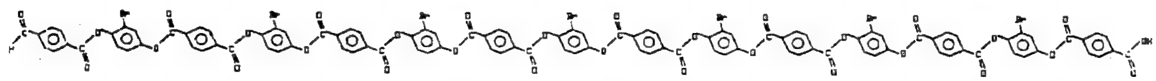
Tracy Reed				7/1/94
LCP 2x4 Burst Test Data				Notes/Failure Mode
Material	Pressure (psi)			[illegible] machined motors were thin side down
B950-1				No peak,, no data printed. Loose fitting. Pinholes.
B950-2	358	Mean:	4.38E+02	Cracked along the seam.
B950-3	469			Cracked along the seam.
B950-4	486	Std. Dev.:	6.95E+01	Cracked along the seam.
A950-1	1670			Good, rectangular patch.
A950-2	1430	Mean:	1.55E+03	Good.
A950-3	1240			Good.
A950-4	1840	Std. Dev.:	2.64E+02	Good.
A950-5M	197			Failed along inclusion on the interior.
A950-6M	180	Mean:	2.06E+02	Failed along inclusion.
A950-7M	241			Failed along inclusion.
A950-8M	205	Std. Dev.:	2.57E+01	Failed along inclusion.
B420-1	457			Rectangular patch is right along seam.
B420-2	730	Mean:	5.07E+02	Good, near seam.
B420-3	427			Good, near seam.
B420-4	415	Std. Dev.:	1.50E+02	Good, near seam.
B420-5M	337			Whole side blew out.
B420-6M	376	Mean:	3.59E+02	Good
B420-7M	344			Good
B420-8M	377	Std. Dev.:	2.10E+01	Whole side blew out.
B230-1	1130			Good
B230-2	1320	Mean:	1.26E+03	Good
B230-3	1160			Good
B230-4	1440	Std. Dev.:	1.45E+02	Good
HX4000-1	381			Cracked

Models of liquid crystal polymers, drawn in Autocad.

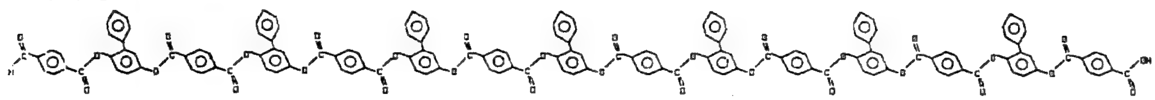
HQTA



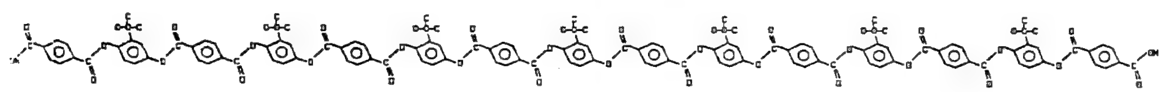
BrHQ



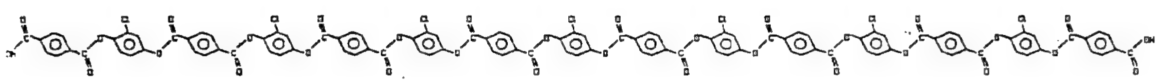
PHQ



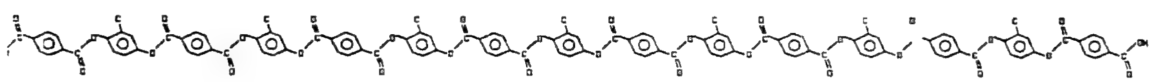
TBHQ



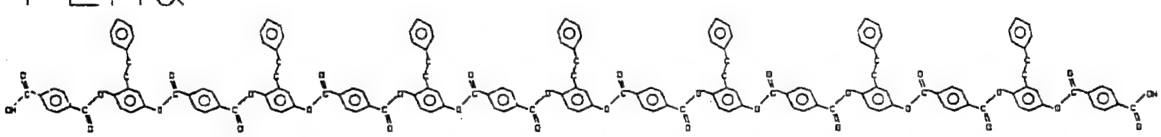
ClHQ



MHQ



PEHQ



Solid propellant processing sheet used to mix the propellant used in the Academy motor.

SOLID PROPELLANT PROCESSING SHEET			HAZARD CLASS:
MIX NUMBER: ACADM-	ENGINEER: REED Y5416	OPERATOR:	BATCH NUMBER:
MIXER SIZE: 1 gallon	CELL USED:	BATCH SIZE: 6500g	DATE MIXED:

MATERIAL	%	GRAMS	WEIGHT			LOT NO. & NOTES
R45M	10.46	679.9	N	T	G	905175
DOZ	2.15	139.75	N	T	G	
DDI	2.39	155.35	N	T	G	
			N	T	G	
Carbon Black	0.20	13.0	N	T	G	
AP (400 mc)	30.65	1992.25	N	T	G	
AP (200 mc)	30.65	1992.25	N	T	G	
AP (25 mc)	23.50	1527.5	N	T	G	
			N	T	G	
			N	T	G	
	.	.	N	T	G	
	.	.	N	T	G	
	.	.	N	T	G	
	.	.	N	T	G	
	.	.	N	T	G	

MIX INFORMATION
TOTAL MIX TIME: 1 HRS MIN
EOM VISCOSITY @ 1/SEC = kp
SOLVENT: CYCLOHEX

PROCESSING STEP	SPEED OF RPM	TIME (MIN) MIXING	START	STOP	VACUUM NO/YES	mmHg	TEMP °F	INSTRUCTIONS
1. ADD FIRST INGREDIENTS	300	10 MIN					140	R-45M/DOZ/Carbon Black
2. ALL 400 & 50% 200mc AP	300	15 MIN					140	
3. ADD 50% 25 mc AP	300	15 MIN					140	
4. ADD 50% 25 mc AP	300	15 MIN					140	
5. ADD 25% 200 mc AP	300	15 MIN					140	
6. ADD 25% 200 mc AP	300	15 MIN					140	
7. ADD DDI	300	2/15 MIN					140	
8. CAST								

MOLD: At least 10 Academy Motors

CURE OVEN: IN OUT

Acknowledgments

I would like to thank Dr. John Rusek for being my mentor and for providing me with the opportunity to work on this project as well as for all of the time he has put into teaching me so much. I would also like to thank Dr. David Elliott of Arkansas Tech University for his advice on engineering matters. I also want to thank Dr. Kevin Chaffee and Dr. Pat Mather for their support and encouragement throughout the summer.

MATERIALS ENGINEERING SECTION
SCIENCE & ENGINEERING LABORATORY BRANCH
McCLELLAN AIR FORCE BASE, CALIFORNIA

CHARRED PLASTIC TUBE SPECIMEN

SUBMITTED BY: TIEC/Mr. Frank DATE: April 8, 1992

1. **INTRODUCTION:** We were requested to section and microstructurally evaluate a plastic tube which had been exposed to burning fuel. The intent was to determine the type of damage to the tube and the structure of the char.

2. **SPECIMEN DESCRIPTION:** The as-received specimen is shown in figure 1. The specimen consisted of one-half of a longitudinally sectioned tube. One end of the specimen showed a large amount of char, although the specimen had been exposed to heat all along the inner surface. The end with the large amount of char was of primary interest; figure 2 shows a magnified view of this end. The char was highly porous and showed many thin flakes.

3. **EXPERIMENTAL:** The charred end of the tube was encapsulated with a epoxy mounting compound, with a fluorescent dye added, to support the char. This end of the tube was then sectioned into three samples which were encapsulated into discs, ground, and polished for examination. Figure 3 shows the location of the polished side of the samples identified as A, B, and C. In addition, longitudinal and transverse (cross-section) samples from the injection end of an unburned tube were cut and polished for comparison.

4. **RESULTS:**

a. Figures 4 and 5 show the longitudinal and transverse sections from the unburned tube, respectively. Several large pores are visible in both photographs. The pores were located in two different locations: 1) near the center-thickness and 2) near the inner diameter edge. There were several large cracks present. The plane of these large cracks was perpendicular to the axial direction, as shown in figure 6. The cracks spanned from 30 to 70% of the thickness. The cracks were preferentially, but not exclusively, located at large pores. There were many somewhat smaller cracks at the injection corner, as shown in figure 7. There were several small cracks located within 5% of the thickness from the outer or inner diameter edges. In contrast to the other cracks, the plane of these small cracks was primarily axial. Figure 8 shows an example. Figure 8 also best shows what we will call flow lines near the inner edge. These flow lines are really planar in character, since they are visible in both longitudinal and transverse sections. At higher magnifications, in many, but not all areas a lamellar microstructure was visible, as shown in figure 9. In most cases, the orientation of the lamella was perpendicular to the axis of the tube.

b. Figures 10, 11, and 12 show the polished surfaces of samples A, B, and C, respectively. The epoxy used to encapsulate the sectioned specimens did not have the fluorescent dye added, consequently, it is much lighter in these figures than the epoxy supporting the char.

c. All three samples showed all of the same types of defects found in the unburned sections. These defects included large pores near the

centerline, large pores near the inner diameter, and cracks transverse to the axial direction, although these cracks were smaller than those found in the unburned sections. In addition there were small cracks near the inner and outer surfaces, similar to those shown in figure 8. The samples also exhibited the lamellar microstructure shown in figure 10 in many areas.

d. Some of the large pores near the inner diameter in samples A, B, and C were caused by the evolution of gases within the plastic as the burning fuel raised the temperature of the plastic. This was indicated by local changes in flow line direction associated with porosity, as shown in figure 13, and elongated and stretched plastic material.

e. The structure of the char is of primary interest in this evaluation. Figures 13 and 14 show some of the charred area in samples A and B, respectively. The green areas of the photos are the epoxy encapsulant with the fluorescent dye added; the black areas are the char. The large amount of porosity in the plastic adjacent to the char is visible, and the highly porous nature of the char is evident. The char consists of membranes of decomposed plastic enclosing gases evolved by the decomposition. The membrane structure of the char may be related to the planar character of the plastic which is indicated by the flow lines of figure 8. Different regions of the char itself was apparently in different stages of decomposition. Figures 15 and 16 show exactly the same area of sample A with exactly the same magnification; only the illumination was different. Figure 15 shows the area with oblique light; the overall shape and size of the char is apparent. Figure 16 shows the area with the light perpendicular to the surface. The areas of the char furthest away from the plastic show pieces which are much more reflective. We believe that the more reflective pieces are plastic material which has been graphitized. This opinion is based largely on the fact that fibers of polished graphite-epoxy composite samples are also very reflective under this type of lighting. Figure 17 shows a higher magnification view of one of these more reflective areas.

5. CONCLUSIONS:

a. Damage to the tube from the burning fuel included decomposition, pore formation, and plastic deformation.

b. The tube was significantly flawed in the as-manufactured condition, with large pores and both large and small cracks.

c. The char had an expanded, membrane structure, with some regions of apparent graphitization. The membrane structure of the char may be related to the planar character of the plastic.

Charred Plastic Tube Specimen

9 Atch
1. Fig 1, Fig 2, Photos
2. Fig 3, Sketch
3. Fig 4, Fig 5, Photos
4. Fig 6, Fig 7, Photos
5. Fig 8, Fig 9, Photos
6. Fig 10, Fig 11, Photos
7. Fig 12, Fig 13, Photos
8. Fig 14, Fig 15, Photos
9. Fig 16, Fig 17, Photos

John M. Meininger M/C
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Materials Engineer

William F. Emmons
William F. Emmons 0 9 APR 1992
Chief, Materials Eng. Sec.

REVIEW
This report has been reviewed and is approved.

Richard R. Millward
Richard R. Millward 0 9 APR 1992
Chief, Science & Engineering Lab
Tech & Ind Support Directorate

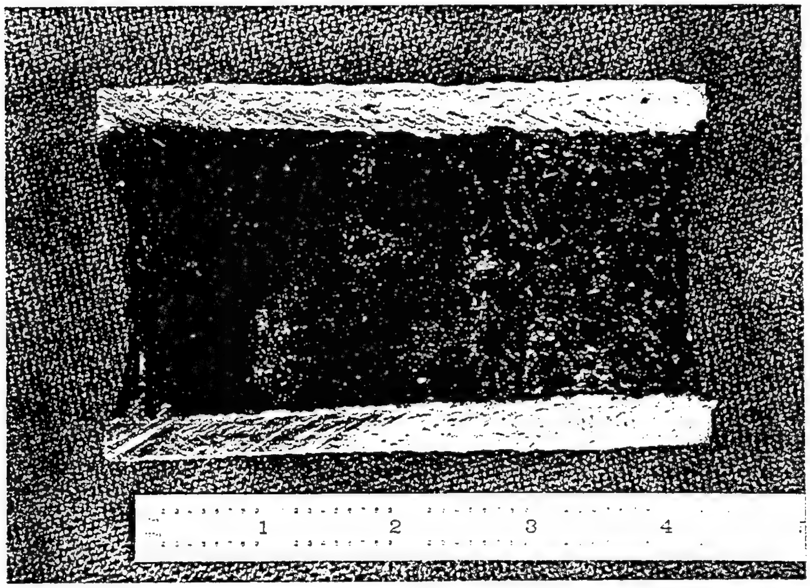

Figure 1. Specimen as received showing large amount of char on one end.

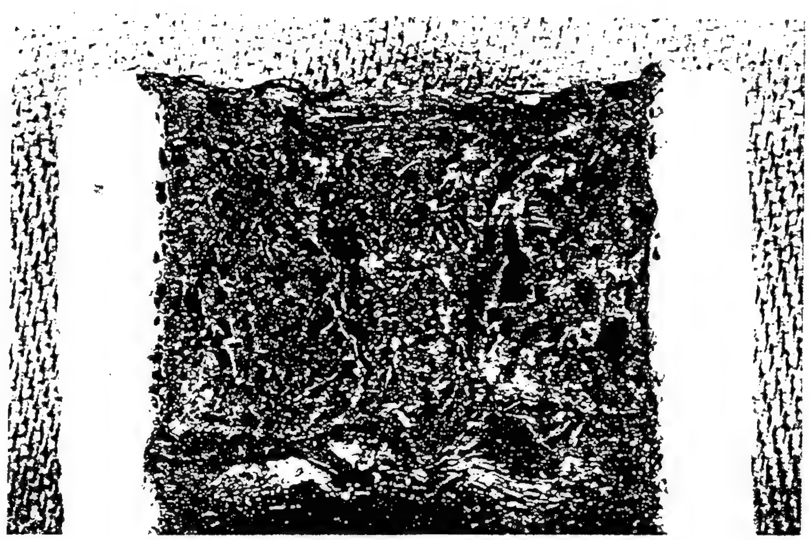

Figure 2. Magnified view of charred end showing porous structure with many thin flakes.

Atch 1

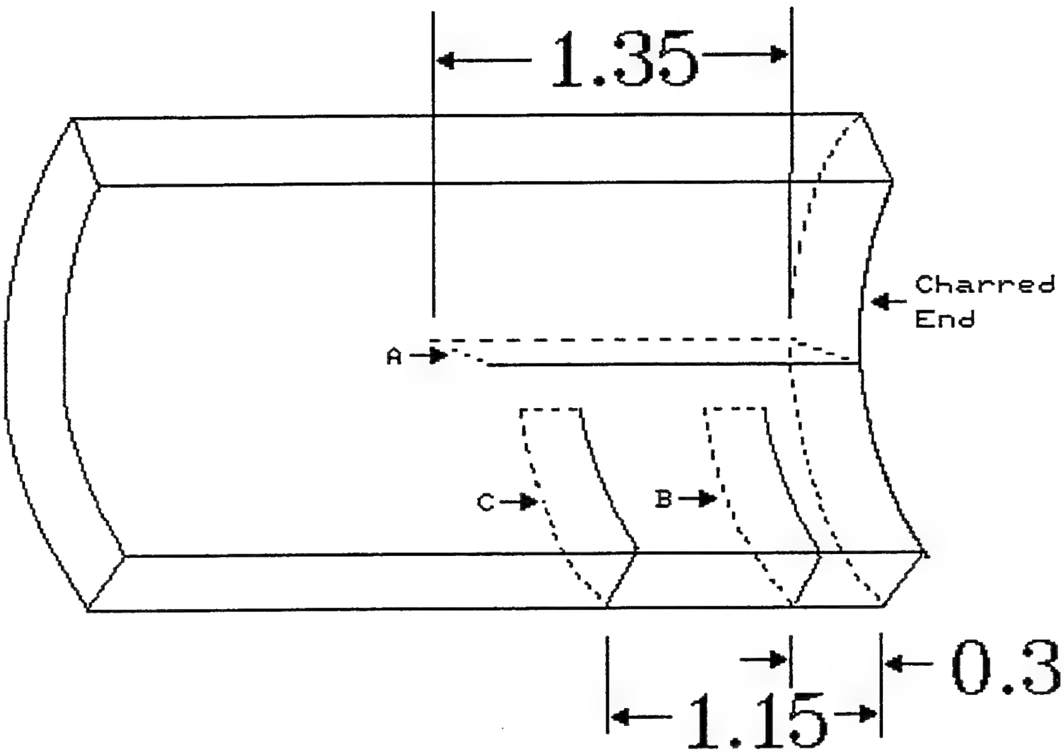

Figure 3. Sketch showing locations of polished sides of samples A, B, and C.

Atch 2

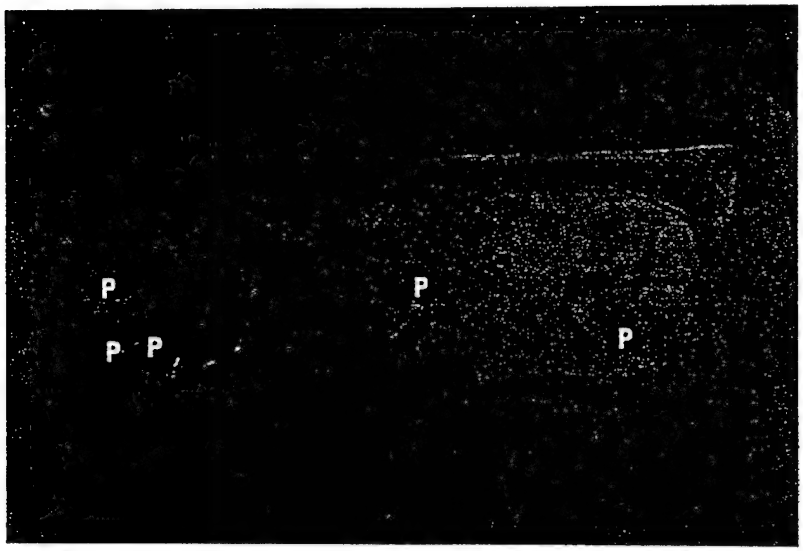

Figure 4. Longitudinal section of unburned tube. Examples of large pores are identified by "P." Large cracks are also visible. Magnification: 4.8X.

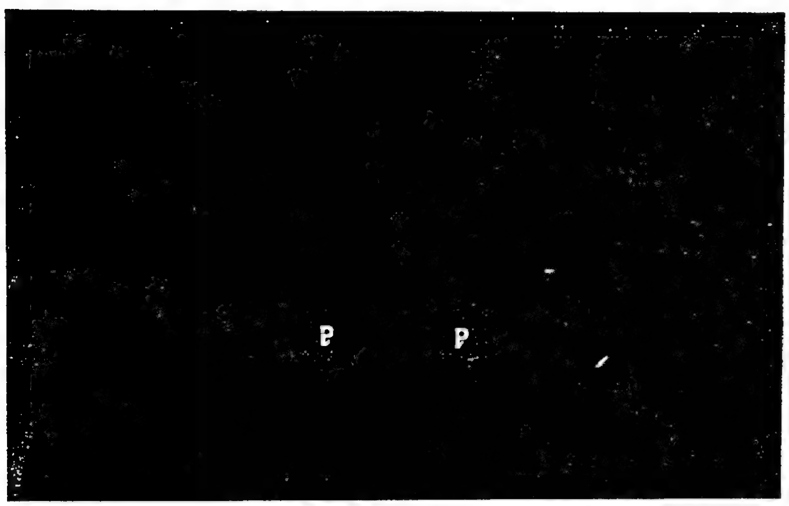

Figure 5. Transverse (cross) section of unburned tube showing examples of porosity identified by "P." Magnification: 4.8X.

Atch 3

Figure 6. Longitudinal section of unburned tube showing large cracks. Magnification: 9.6X.

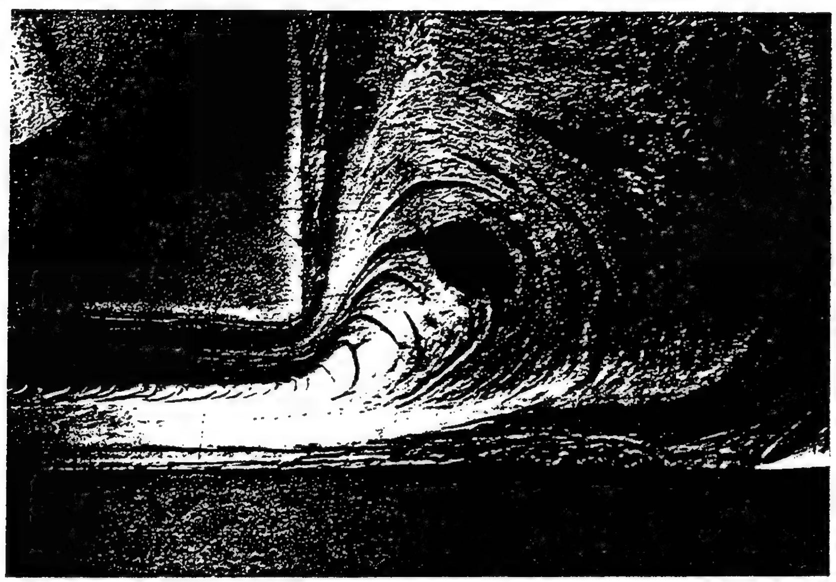

Figure 7. Longitudinal section of injection corner of unburned tube showing many smaller cracks. Magnification: 9.6X.

Atch 4

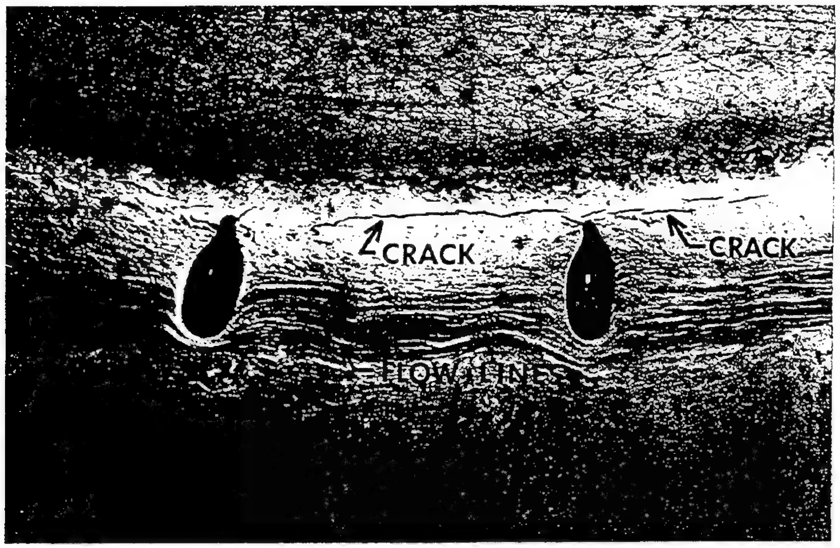

Figure 8. Transverse section of unburned tube showing small cracks near inner diameter edge. Magnification: 12.8X.

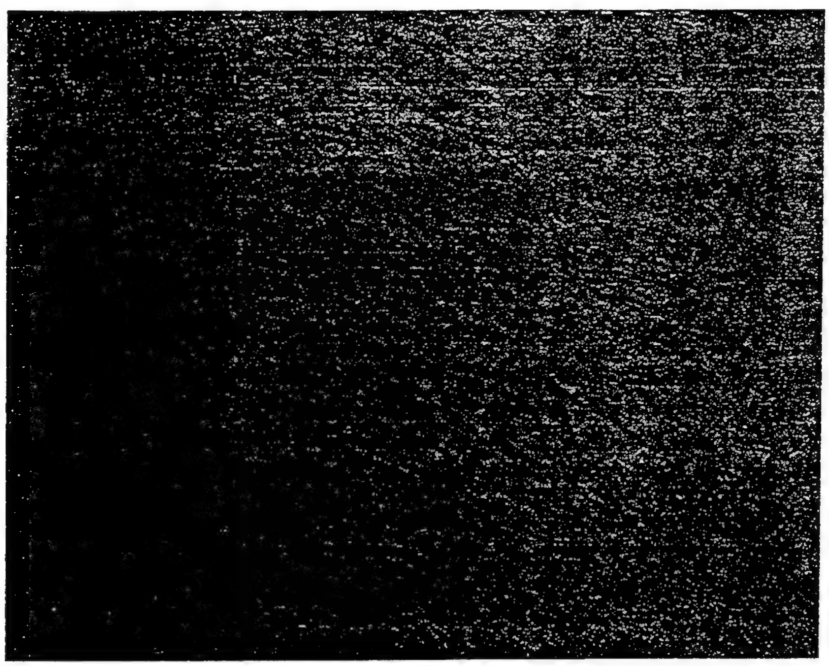

Figure 9. Longitudinal section of unburned tube showing lamellar microstructure. Magnification: 200X.

Atch 5

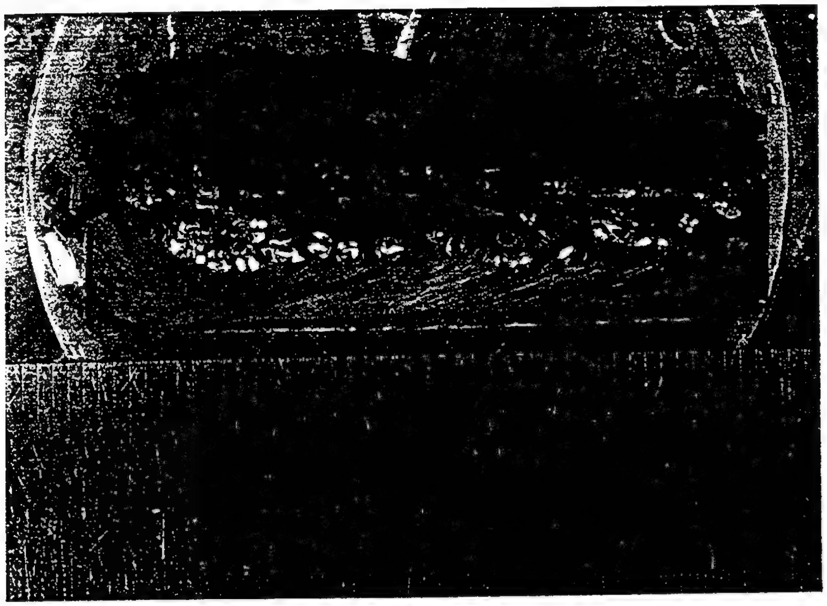

Figure 10. Encapsulated sample A showing porosity of plastic along inner edge and near center of thickness.

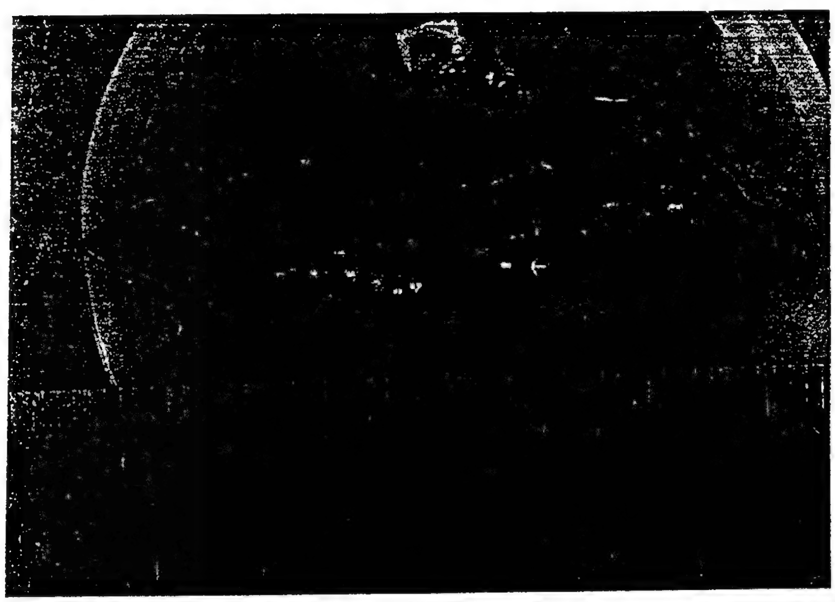

Figure 11. Encapsulated sample B showing porosity of plastic along inner edge and near center of thickness.

Atch 6

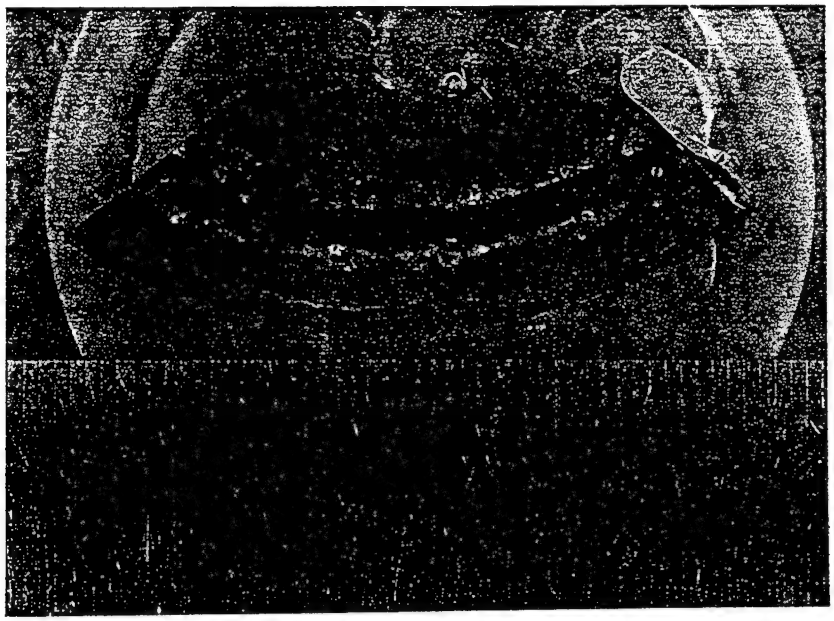

Figure 12. Encapsulated sample C showing porosity in plastic along inner edge and near center of thickness.

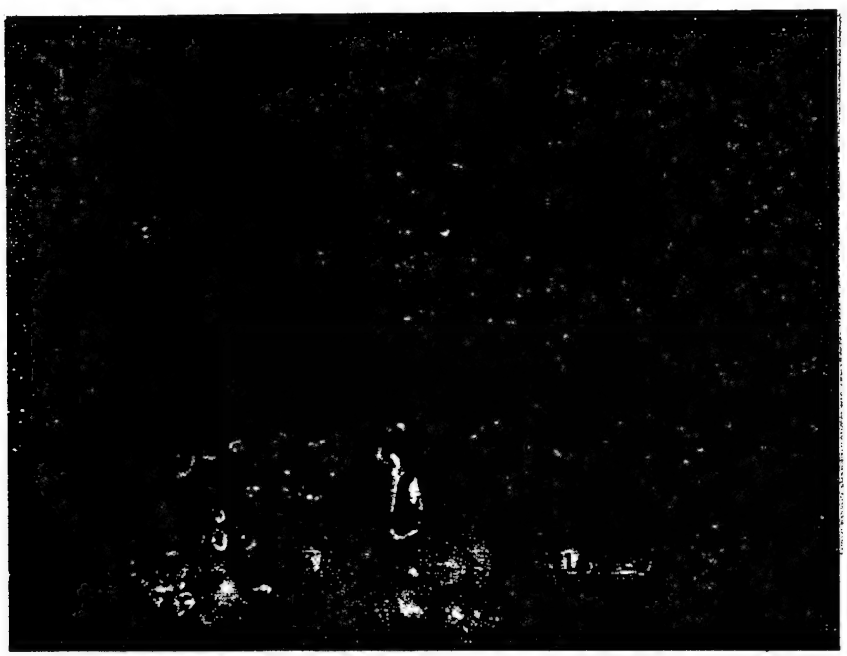

Figure 13. Charred region of sample A showing the porosity of the char and of the plastic. Also shown is a change in the flow line direction, indicating plastic deformation. Magnification: 9.6X.

Atch 7

Figure 14. Charred region of sample B showing the porosity of the char and of the plastic. Magnification: 9.6X.

Figure 15. Area of sample A showing overall shape and size of char. Photo taken with oblique lighting. Same area as figure 16. Magnification: 25.6X.

Atch 8

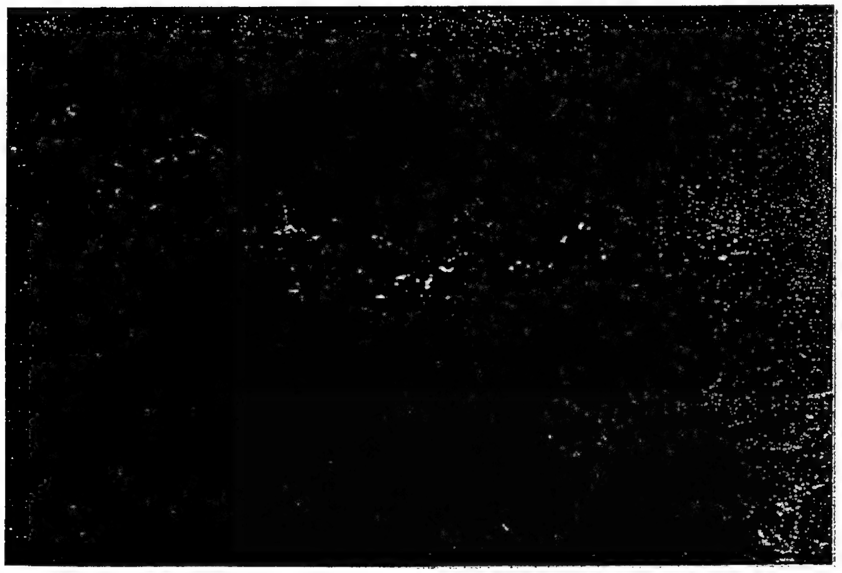

Figure 16. Area of sample A showing reflective pieces of the char. Photo taken with perpendicular lighting. Same area as figure 15. Magnification: 25.6X.

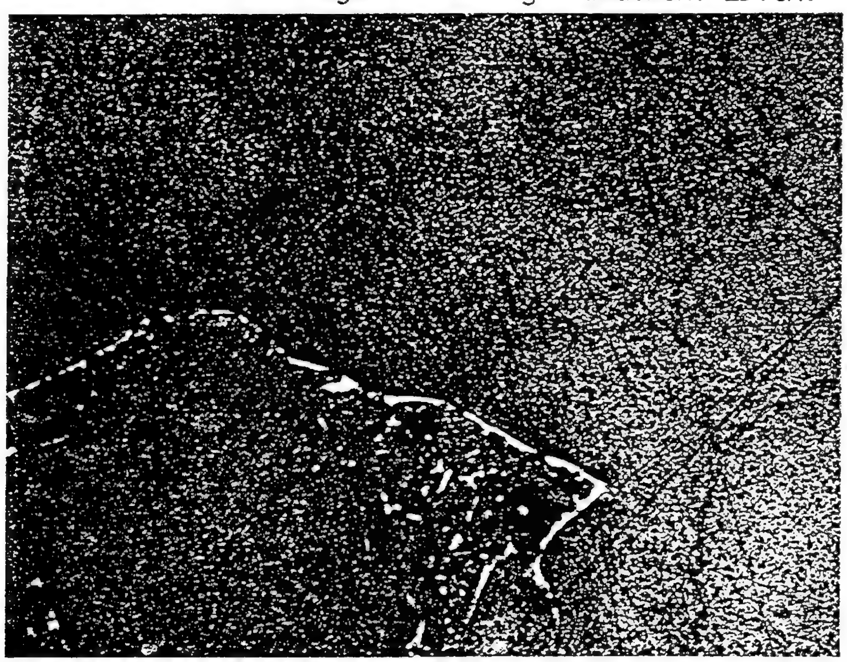

Figure 17. Area of sample A showing reflective pieces of the char. Magnification: 100X.

Atch 9

SOLID ROCKET PROPULSION APPLICATIONS FOR ADVANCED POLYMERS

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ABSTRACT

The demands of lowering the cost and increasing the reliability of solid rocket propulsion systems have forced the aerospace industry to investigate new materials and fabrication techniques. The performance specifications for stiffness, strength and temperature resistance make continually finding better materials and processes quite challenging. Advanced structural plastics, such as liquid crystalline polymers, may meet these requirements. The Astronautics Laboratory initiated an in-house program to determine if advanced polymers could meet the cost/performance/reliability requirements. Components identified for polymer application includes motor cases, ignitor housings and nozzles. Injection molded parts, fabricated from VECTRA(R), XYDAR(R), ULTEM(R) and RYTON(R) were designed and tested. In addition, CELAZOLE(R) was also tested. An overview of this program and the progress to date is presented.

INTRODUCTION

The design impetus for most solid rocket propulsion components has been performance. The performance criteria has driven the industry to develop extremely strong and extremely lightweight components. By reducing the inert component weight, the amount of propellant can be increased thereby increasing the motor performance. For rocket motor cases, DCA6 steel and graphite epoxy have been used becuase they yield the desired high strengths and low weights. Material and fabrication costs, however, tend to be quite high.

The complexity of the fabrication processes using these materials can lead to high component rejection rate or components that vary significantly in terms of mechnical properties and structural integrity. By comparison the bulk cost of liquid crystalline polymers is quite low. Material properties can be tailored to the application by heat treatment or by adding fillers. A variety of low cost fabrication techniques including injection molding, pultursion, compression molding and resin transfer molding can be used to make net shap parts in one step.

This paper presents the rocket propulsion applications identified for these materials, as well as the progress to date. This is a combined Air Force effort with the Air Force Logistics Command at McClellan and Hill AFB, the Air Force Armament Laboratory (AFATL) and the Air Force Institute of Technology (AFIT) assisting us.

THEORY

Liquid crystalline polymers (LCP's) can be subdivided into two classes; thermotropes and lyotropes. Thermotropic LCP's exhibit liquid crystalline behavior in the melt, while lyotropic LCP's are liquid crystalline in solution. Examples of thermotropes include VECTRA (R), HX4000(R) and GRANLAR(R), all of which exhibit

an isotropic/nematic phase transition above 300 C. Typical lyotropes include KEVLAR (R) and polybenzthiazoles, polybenzoxamides and polybenzimidazoles. KEVLAR (R) exhibits liquid crystalline behavior in sulfuric acid while the other three polymers are drawn from polyphosphoric acid, where they behave as nematic LCP's.

In general, the molecular architecture is the prime determinant in liquid crystalline behavior. LCP's are rigid rod polymers, usually polyesters which have a molecular "aspect ratio" of 30:1. This implies a typical length of 90 A and a typical degree of polymerization of 10. Lyotropes generally have many barriers to rotation due to molecular geometry, steric barriers and buried polar moeities. Polybenzoxazole, a typical lyotrope, is depicted in Figure 1.

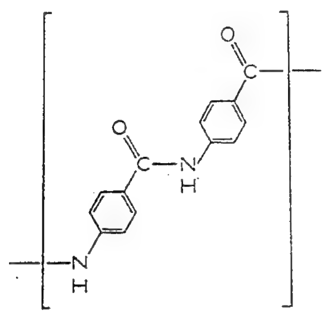


FIGURE 1. LYOTROPE STRUCTURE

Thermotropes generally contain large pendant groups, no buried polar species and are more free to rotate around the backbone centerline. A typical thermotrope is depicted in Figure 2.

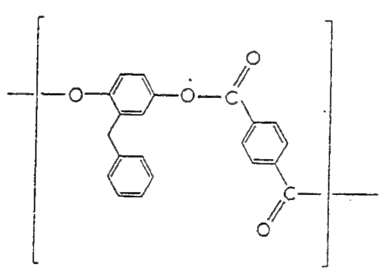


FIGURE 2. THERMOTROPE STRUCTURE

An interesting phenomena has been observed in recent years within the class of thermotropes: annealing. A given thermotrope is injection molded into a cylindrically symmetric part as an unfilled resin. This part is then subjected to a long duration temperature cycle after which the part will behave as a thermoset. This phenomena is not well understood and is being explored intensely by the Air Force laboratories. Materials which "anneal" clearly would have great application as high temperature solid rocket case and nozzle materials as well as liquid rocket engine component materials.

APPLICATION IDENTIFICATION

The purpose of the Advanced Polymer Component (APC) program is to utilize the benefits of these polymers in the development of rocket components. Figure 3 presents the interrelationship between this program to other AL in-house research programs. We feel that the potential applications of these polymers is great.

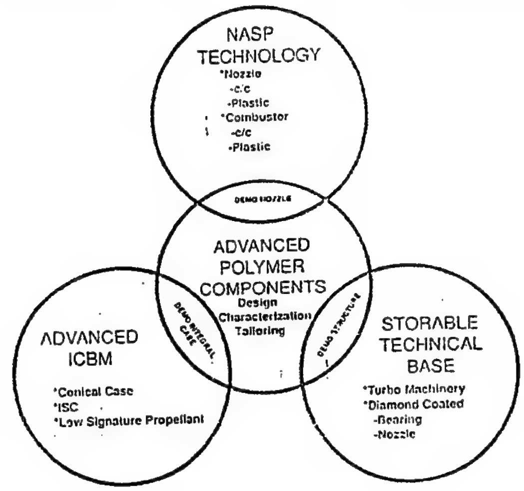


FIGURE 3. ASTRONAUTICS LABORATORY PROPULSION IN-HOUSE INITIATIVE RELATIONSHIP

This paper focuses on solid propulsion motor applications . Figure 4 presents at generic solid rocket motor. The inert components, such as the motor case and nozzle make uo the majority of the total weight and cost of the motor. When the case skirts and interstages are added to the motor, the weight and cost contribution of the inert components is futrther increased. When these components are made from advanced composites such as graphite-epoxy, the labor costs associated with the fabrication make up the majority of the costs. By using the LCPs low cost fabrication techniques, such as injection molding, for the various components can be applied.

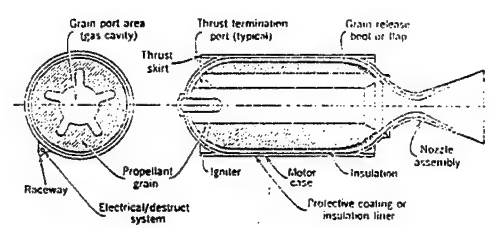


FIGURE 4. GENERIC SOLID ROCKET MOTOR SCHEMATIC

In theory, the LCPs have potential for motor case applications. Figure 5 presents a graph showing where the LCPs rate relative to other case materials. It is highly desirable to have a material that is extremely strong and extremely stiff. As shown in the figure, the LCPs approach this desired goal. For this reason, a majority of the solid rocket work using LCPs concentrate on motor case applications. Some nozzle application work was also performed.

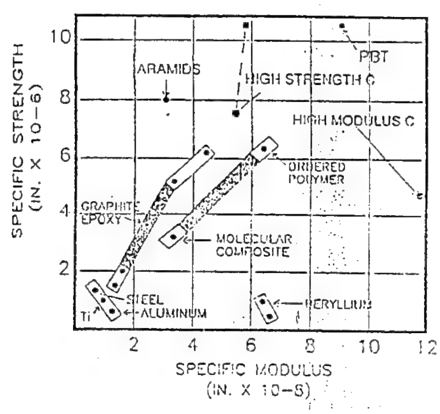
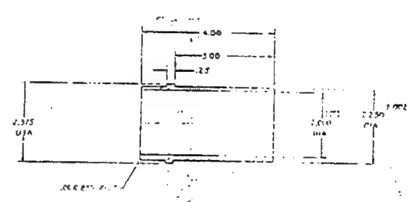


FIGURE 5. MATERIAL STRENGTH VS. STIFFNESS COMPARISON

PLAN OF ATTACK

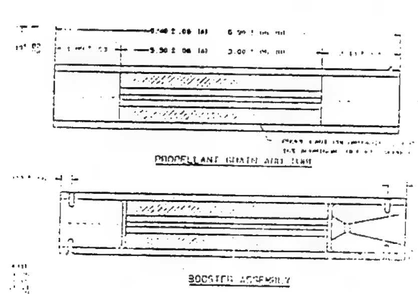
With the case and the nozzle applications identified, a work plan was developed. Because the AL is a newcomer in working with polymers, the most logical plan was to develop "simple" motor cases initially. Depending on the success of the "simple" motor case development, more complex cases would be developed using the LCPs.

Figures 6-9 present the motors case applications we are pursuing. Figure 6 is our "2x4" motor, which is used for obtaining propellant ballistic property data. The operating conditions are listed with the figure. These cases would be compression molded and injection molded from the various LCPs, in particular the various grades of VECTRA. Figure 7 shows the Air Force Academy Motor and it's operating conditions. Notice the increasing complexity of the motor cases. The LCP design for Academy Motor case would be a two-part design vs. the current three part design.



MAX CHAMBER PRESSURE: 2000 PSI
(HIGH PRESSURE TESTING, 12,000 PSI
MAX CHAMBER TEMP: 3700 K
MAX BURN TIME: 1 SEC

FIGURE 6. 2X4 TEST MOTOR

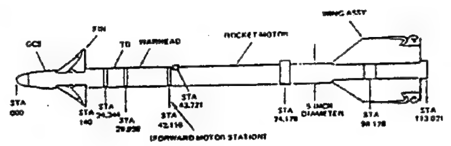


CHAMBER PRESSURE: 300-400PSI
1000 PSI (MAX)
CHAMBER TEMPERATURE: 3300 K
MAX VERTICAL LOADS: 15 GS
BURN TIME: 2.1 SEC

FIGURE 7. AIR FORCE ACADEMY MOTOR

For this motor case, the head-end closure and the motor case would be incorporated into one piece.

Figures 8 and 9 present more ambitious applications of these materials. The AIM-9L "Sidewinder" short range air-to-air missile is shown in Figure 8. The design of this motor case presents many challenges. Not only does the motor case have to survive the flight environment (up to Mach 8 with a 35 g turn capability), but it has to survive captive carry and handling loads. We selected the wing tip location of an F-16 (shown in Figure 10) as the design condition. Thermal conditions of -45 F to 145 F will be considered, as well as the associated transmitted moments and forces. We will try to design the launch lugs "into" the motor case. This means that we will try to eliminate the launch lug "bands" that are currently used on the AIM-9s. We hope to use the information we gain from this design for a new generation short range air-to-air missile design.



- 5 " O.D., 71" LONG (MOTOR)
- 40 SECOND FLIGHT TIME (MACH 4)
- -45F TO 145F TEMP SURVIVABILITY
- AEROHEAT UP TO 800F

FIGURE 8. SIDEWINDER MISSILE

The most attractive feature of the LCPs for tactical motor applications is the potential insensitive munitions application. The mechanical properties of these materials degrade at significantly lower temperatures than current tactical motor case materials. At 600 F, the mechanical properties degrade to a point that a motor case made from these materials will lose all structural integrity. This attribute, coupled with the LCP's inherent high strength and stiffness and low cost fabrication methods, have a high potential of being an ideal material for tactical motor case applications.

As shown in Figure 3, we are currently developing, demonstrating and integrating advanced, low cost solid propulsion technologies for a new generation intercontinental ballistic missile (ICBM). Our first look at applying LCPs to ICBMs have given us several ideas. Figure 9 presents the candidate areas. Possibly the most ideal areas are the polar boss, ignitor housing and interstage. The most interesting application is for external protection of the various stages. A common LCP, KEVLAR, is used for bullet-proof vests. We hope to demonstrate that low-cost molded sheets of LCPs are viable materiels for the debris impact and thermal external protection environments.

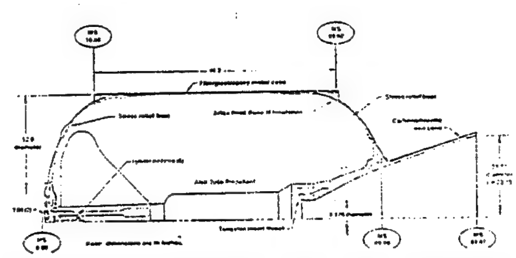
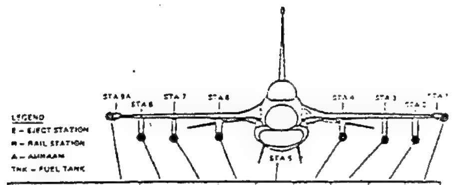


FIGURE 9. INTERCONTINENTAL BALLISTIC MISSILE MOTOR



STATION NUMBER	9	8	7	6	5	4	3	2	1
TYPE STATION	R	R	R	TNK	TNK	TNK	R	R	R
AMRAAM STATION	A	A	A				A	A	A

FIGURE 10. F-16 STORES LOCATION

LOW COST FABRICATION METHODS

Polymer components have been fabricated by a variety of low-cost methods. These methods have been extensively developed by the toy and automotive industry. In addition, the Air Force Armament Laboratory (AFATL) has a contracted effort with McDonnell Douglas in St. Louis to investigate a variety of low cost composite fabrication methods for tactical weapon applications. The authors refer the reader Ms. Debbie Westfall at AFATL for complete information on this program. This section will present a brief summary of the methods that they have investigated.

We surveyed the "Big 3" automakers on polymer components fabrication and design techniques. The "Big 3" have formed an Automotive Composites Consortium to develop a data base on this information. We are currently supplying them with LCP mechanical properties data that we are obtaining. The automakers requirements for low cost structural composites are quite similar to the aerospace industry's desires with one exception. They are interested in a fabrication process that can produce consistent quality parts very quickly. "Very quickly" in the auto industry means a few minutes. During our recent survey, we found that one automaker rejected a fabrication process because it was too slow - it took six minutes to produce a quality part!

The two fabrication processes that we have been concentrating on are injection molding and structural resin transfer molding. Having investigated most of the polymer component fabrication techniques, including compression molding and pultrusion, we felt that injection and resin transfer molding have the most promise for fabricating parts that meet our requirements.

Figure 11 presents a schematic of an injection molding machine. This machine melts the polymer pellets by resistance and shear heating. The shear heating is the main contributor to melting the polymer pellets. The polymer is continually "worked", such that all the air is removed. Once a predetermined amount of melted polymer fills the "breech" section, it is shot into the mold. After a pre-determined clamp time, the mold is opened and the finished part is removed.

While the injection molding process seems simple, there are many variables that are dependent on the type of polymer being injected. Screw speed, resistant heating temperature, clamp time and clamp pressures are some of the factors that are "polymer dependent". A majority of the component development time is spent determining these injection molding variables. Once these variables are set, the injection molding process will yield consistent high quality parts at an extremely high rate.

There are a few limitations with injection molding. The parts cannot be too large - the cooling rate of the melted polymer is the limiting factor with the component size.

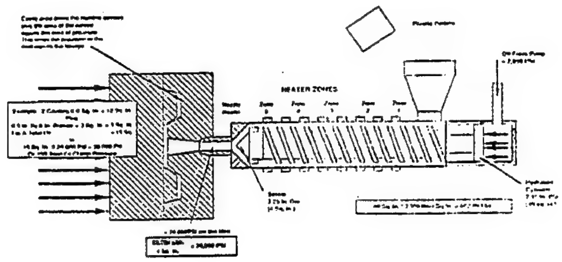


FIGURE 11. INJECTION MOLDING MACHINE

Figure 12 presents a schematic of the structural resin transfer molding process. Much larger parts can be fabricated using the structural resin transfer molding process. In addition, the fiber net allows for a considerably stronger structure than what injection molding can yield. This process is will yield large, complex shape, large parts.

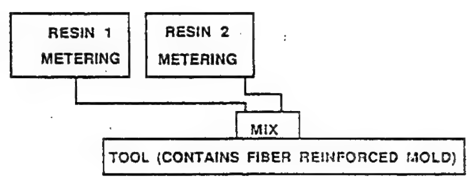


FIGURE 12. STRUCTURAL RESIN TRANSFER MOLDING PROCESS

PROGRESS TO DATE

Both feasibility demonstrations and design data generation have been the emphasis of the progress to date. This two-prong approach was taken because some immediate "feasibility" applications were identified, such as the 2x4 motor case and the academy motor nozzle. However, we had to check the mechanical properties of the various polymers to establish a data base for us to design from. While the various vendors have published tensile strength data, we needed to verify these numbers prior to any extensive design.

Figure 13 presents the molded tensile strength specimens that were tested at the Astronautics Laboratory. This "parts" yields three tensile test specimens in the "axial" direction and three in the "transverse" direction. These directions refer to the polymer molecular orientation, which is determined by the direction of the polymer flow in the mold. The "prongs" of the part are the "axial" specimens, while the "paddle" portion contains the "transverse" specimens. The scrap material from these parts were used for propellant/material compatibility testing, which will be discussed later in this section.

The Figure 13 part was molded with VECTRA A625, VECTRA C130 and RYTON. The nomenclature on the VECTRA(R) refer to the type of filler (A is glass, C is carbon) and the amount of loading in the polymer. The advertised tensile strengths of these materials are 24,000 psi, 31,000 psi and 12,000 psi, respectively.

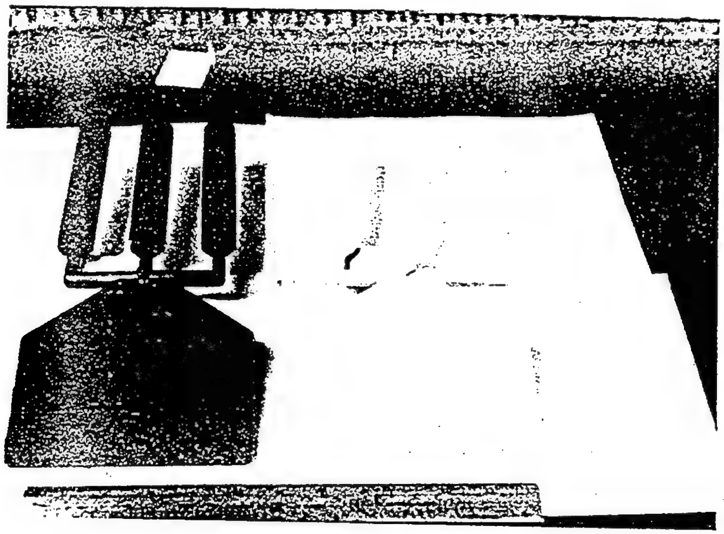


FIGURE 13. POLYMER TENSILE STRENGTH TEST PART

Figure 14 and 15 present the post-test specimens. Notice that tabs were bonded to the ends for the grips. We have just started measuring the mechanical properties and have had some difficulty with the testing. We are detecting a trend that the tensile strength numbers that we are measuring are lower than the published values. These are, however, extremely preliminary numbers.

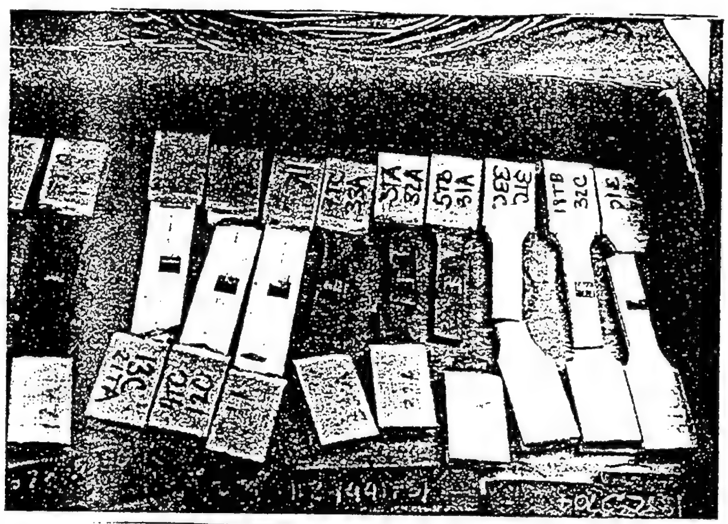


FIGURE 14. POST TEST TENSILE SPECIMENS (TABBED)

The scrap pieces from the "paddle" end of the part were used for propellant/material bonding compatibility tests. Eight samples of each material were used for this testing. Uncured propellant was applied to the surface of these samples. Then propellant was then cured. We would try to peel the propellant from

these samples after cure to determine (albeit in a crude manner) if we had a "good" bond or not. A "good" bond was deemed as when the propellant was extremely difficult to peel from the sample and failed cohesively when the propellant was finally peeled. A "bad" bond was when the propellant neatly peeled from the sample.

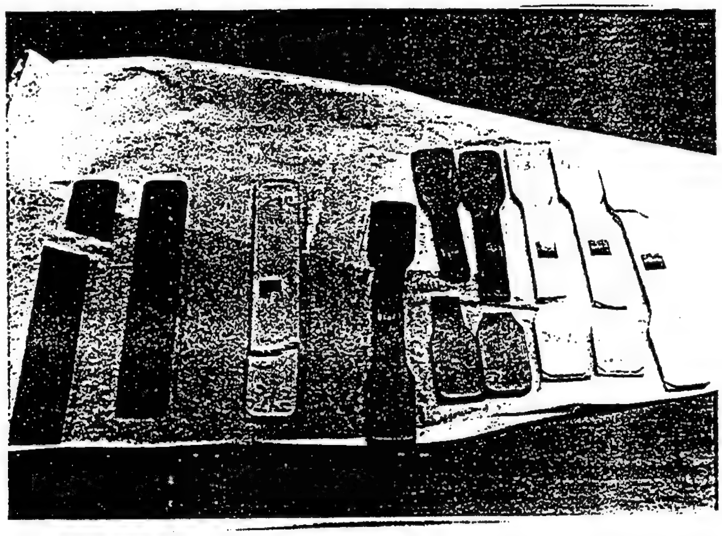


FIGURE 15. POST TEST TENSILE SPECIMENS (UNTABBED)

The surfaces of the samples were treated in the following manner:

- no surface treatment
- surface roughened with sandpaper
- surface coated with N-100 isocyanate
- surface roughed and coated with N-100 isocyanate

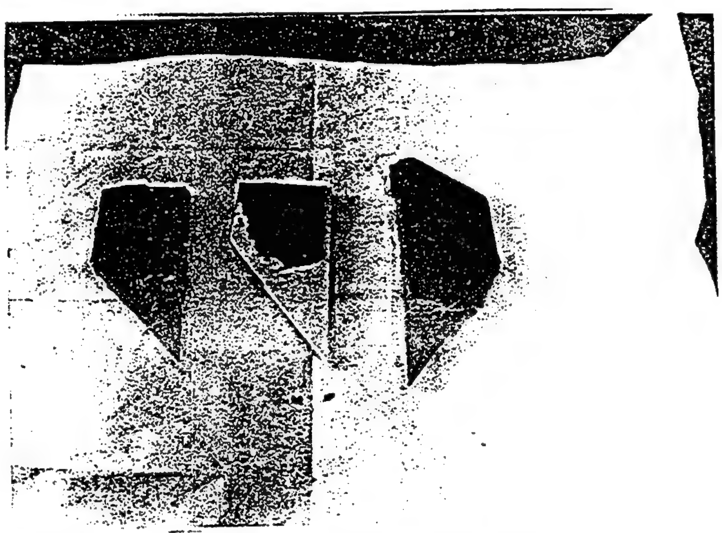


FIGURE 16. "GOOD" PROPELLANT POLYMER BOND

Much to our surprise, most of our test samples yielded good results. Only the samples which did not have any surface treatment yielded bad bonds. Figure 16 presents some of the "good" bond samples. Figure 17 presents a "bad" bond.

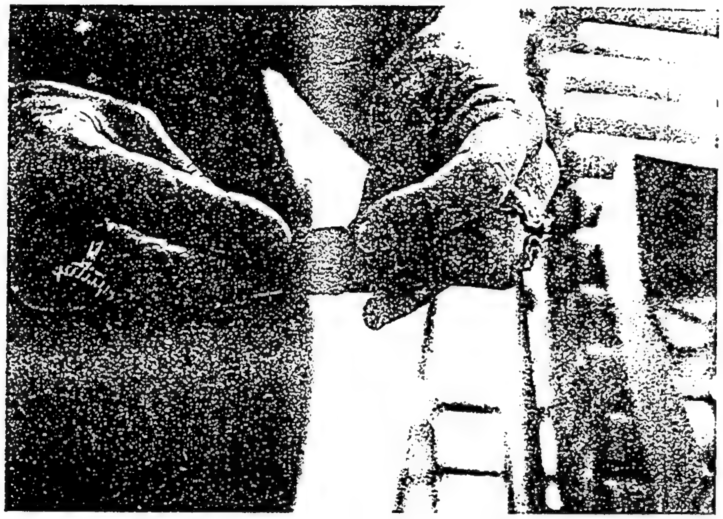


FIGURE 17. "BAD" PROPELLANT POLYMER BOND

The results of this testing gave us the added confidence we needed prior to casting the 2x4 motor cases that were molded from the LCP materials. We felt that we could cast propellant into these cases with a minimum amount of surface treatment.

Figure 18 presents the variety of 2x4 motor cases that we worked with. On the left is our current 2x4 metal case. The one to the right of it is molded from VECTRA C130. Next to that one is one molded from VECTRA A625. Next to that is one that was machined from a billet of LCP material known commercially as CELAZOLE. This material has no known melted point and has to be compression molded and machined to form parts. For our application, we bought existing tube stock and machined the interior to our required dimensions.

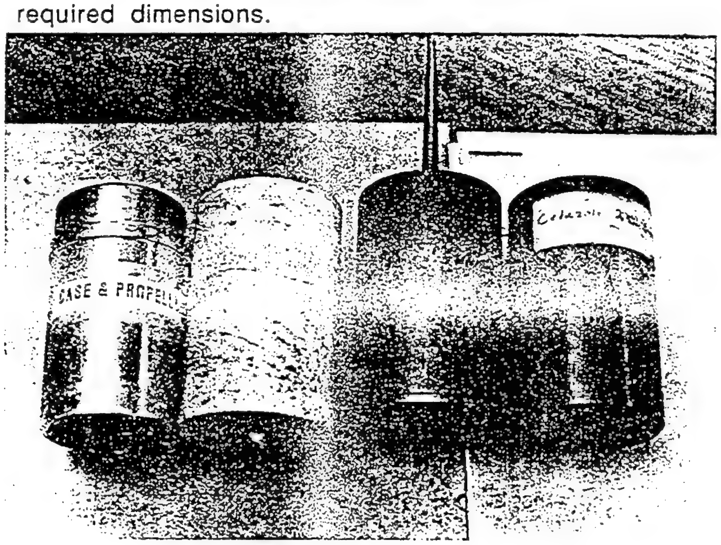


FIGURE 18. 2X4 MOTOR CASES

Figures 19-21 present some of the test results. The wall thickness of the CELAZOLE 2x4 was .250 inches, while the wall thicknesses of the molded parts were .125 inches. The reason for the different thicknesses was that we gave the CELAZOLE 2x4, which we tested first, a healthy margin of safety. We designed the part to

withstand an internal pressure of 7000 psi. After several successful firings, the molded 2x4s were designed for the "low pressure" 2x4 test conditions of 2300 psi. Figure 19 presents the results of two 2x4 motor tests. The CELAZOLE motor, which survived a chamber of pressure of 1200 psi for 1 second, is shown on the right. A VECTRA part which we "plunge molded" at the Astronautics Laboratory is shown on the left. This "Plunge molded" part was full of voids, but we tested it to determine the defect tolerance of using these materials. While the part failed at a void we were surprised to see two things. First was that we were able to recover over two-thirds of the motor case. Second was the char layer which was created when the polymer was exposed to a flame. This char layer would ablate when exposed to a flow field. This char behavior, coupled with the propellant bonding potential of these materials give us great hope that we can use these materials to reduce the number of interfaces in future solid propulsion systems. Figure 21 shows some more of this char behavior on the molded 2x4 motors.

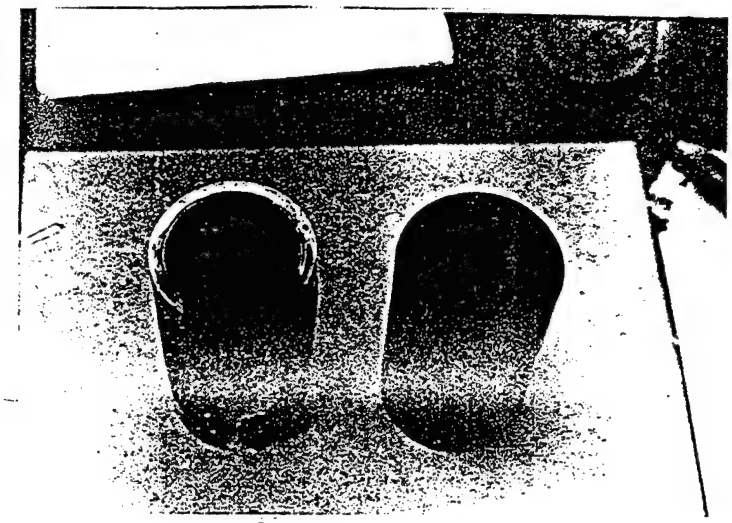


FIGURE 19. CELAZOLE AND VECTRA 2X4 TEST RESULTS

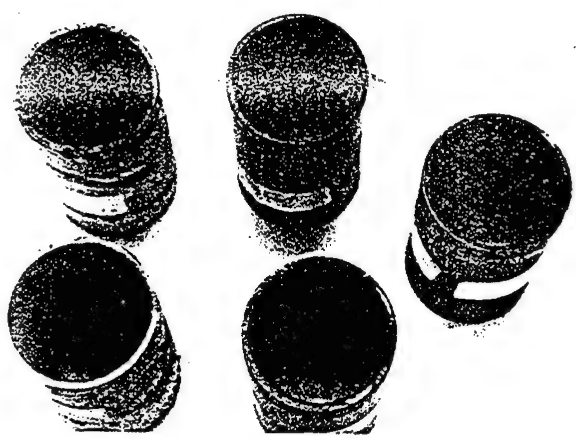


FIGURE 20. INJECTION MOLDED 2X4 MOTOR CASE TEST RESULTS

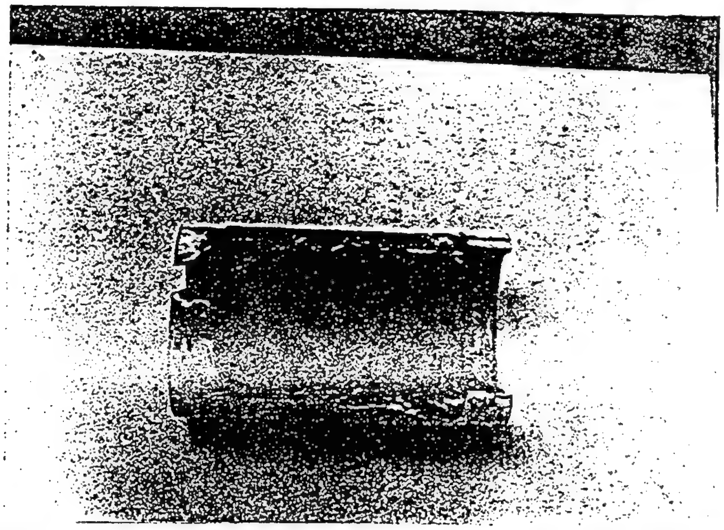


FIGURE 21. CHAR BEHAVIOR FROM VECTRA 2X4 MOTOR CASE

We learned some more about the design limitations of these materials during the molded 2x4 tests. Figures 22 and 23 show some of the successful and not-so-successful tests. We used the published mechanical properties data when we designed the mold for these parts. In theory, these parts should have withstood a chamber pressure of 2300 psi. They failed at chamber pressures of 1000 psi. Discussing these test results and the mechanical properties test results with engineers from the "Big 3" automakers, we found that as a rule, the engineers usually design to 65% of the published mechanical properties. While we are still learning to work with these materials, this will be good rule of thumb for our first cut designs.

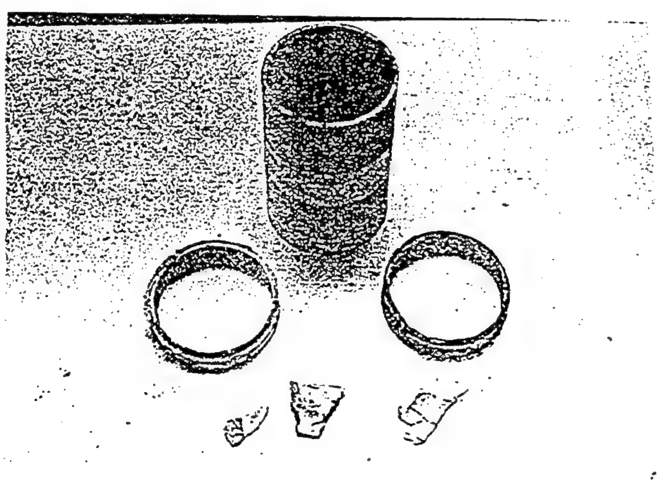


FIGURE 22. VECTRA A625 INJECTION MOLDED 2X4 TEST RESULTS

Figure 24 presents some nozzle tests that we performed using CELAZOLE nozzles. Using the Air Force Academy motors, we exposed these nozzles to 650-800 psi for 4-5 seconds. Noticed that the recessive behavior of this polymer is similar to

FIGURE 23. VECTRA C130 INJECTION MOLDED 2X4 TEST RESULTS

graphite. This material is stronger than graphite and also has homogeneous properties. While further testing is required, the CELAZOLE material seems to hold some promise as a tactical motor nozzle material.

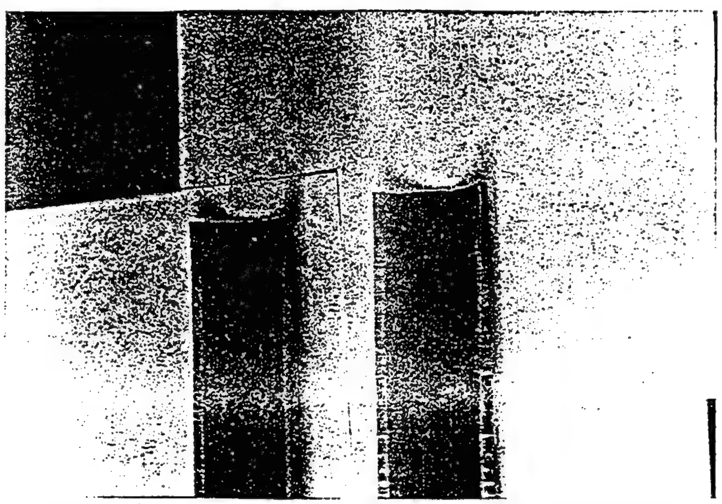


FIGURE 24. CELAZOLE NOZZLE TEST RESULTS

We have recently started a joint motor case design program with the Air Force Institute of Technology, at Wright-Patterson Air Force Base. A group of graduate students will be designing a short range air-to-air motor case using LCP materials. The design requirements are for the wing tip of an F-16. The survivability requirements for this motor case are the same as for the current systems.

SUMMARY/CONCLUSIONS

The test results to date have shown that the Liquid Crystalline Polymers have some great potential for solid rocket applications. Our initial testing have shown that there are some design techniques that need to be used to realize the full potential of these materials. However, we are learning more of these techniques with each design exercise that test.

We encourage any industry and government agency comments on this program. Working in this area in new to us. We welcome any constructive comments.

The amount and quality of the work presented in this paper could not be possible without the help of the following people:

Chris Frank, Rich Griffen, Heiu Nguyen, Pete Huisveld, Jim Trout, Shirl Breitling, Janet Shelley, Tom Duffy, Dave Robinson, Jason Baird, the AL LCP team and the Automotive Composite Consortium.

This paper would not have been possible without their significant contributions.

PROPULSION APPLICATIONS FOR THERMOTROPIC LIQUID CRYSTAL POLYMERS

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Abstract:

The search for stronger, lighter weight, more reliably manufacturable rocket components has led the propulsion industry to examine Liquid Crystal Polymer (LCP) materials for rocket component applications. This paper presents some preliminary research into the applications of LCP's in both solid and liquid propulsion system components. The materials examined are commercially available and general physical property information is presented. Three test articles were fabricated: solid test motor cases, nozzle plugs, and compatibility specimens. A summary of these tests and some of the lessons learned are presented.

Introduction:

The rocket propulsion community is facing some interesting challenges in the near future. With decreasing defense budgets and increasing costs of individual systems, the Air Force is striving to reduce the acquisition costs and total life cycle costs of its rocket systems, both while maintaining performance and improving system reliability. The drive toward lower cost and higher reliability has led the propulsion community to search for new materials and manufacturing techniques for its components. Liquid Crystal Polymers show promise for future propulsion applications. The Advanced Polymer Components project at Phillips Laboratory (AFSC) is studying the application of Liquid Crystal Polymers to rocket motor and engine components. LCP's exhibit high strengths, good solvent resistance, and good thermal stability. Their relatively low coefficients of thermal expansion and good insulating characteristics have led to applications in the electronics industry for computer circuit boards and components. Auto manufacturers have been researching the use of LCP's for under-the-hood components because of their excellent solvent resistance and good thermal stability. These same characteristics make these materials attractive for rocket motor and engine components.

Materials:

The particular materials being researched at the Phillips Laboratory (PL) are thermotropic liquid crystal polymers. Several manufacturers have injection moldable LCP's of this type on the market. Some, not all, of the products are: Xydar (Amoco) , Vectra (Hoechst-Celanese), HX-4000 (DuPont), and Granlar (Montedison). Most of these polymers are marketed as filled injection molding compounds. Common fillers include chopped carbon fibers, chopped glass fibers, and talcs. Phillips Laboratory is researching both filled polymers and neat resins for their chemical and mechanical properties with potential application to rocket components. Table 1 shows a comparison of some of the published physical properties of several advanced engineering polymers. (The Polyphenalene Sulfide (PPS) and Bismaleimide are not LCP's. The information is included only for comparison.)

Table 1 Properties of Some Engineering Polymers[1]

Name	Tensile Strength (Kpsi)	Tensile Modulus (Mpsi)	Heat Deflection Temp (°F)
Vectra B230	35.6	5.4	428
Vectra C130	23.5	2.2	464
HX4000	13.0	3.1	504
Xydar G-430	19.8	2.3	592
Granlar	20.0	1.85	609
PPS (Ryton)	12.0	0.63	N/A
BMI	7.7	0.52	N/A

*AIAA Member

Most LCP's are marketed as filled resins for two reasons: to reduce the inherent physical property anisotropy due to flow shear during molding, and to yield parts with acceptable surface finishes. Early tensile property tests at Phillips Laboratory showed that even filled injection molded LCP's exhibit anisotropy. Test specimens displayed an approximate 30% difference in load carrying capability and tensile modulus between the longitudinally oriented specimens and those oriented transverse to the injection flow direction. Neat resin specimens displayed up to a 60% difference in strength and modulus between the longitudinally and transversely oriented specimens. These differences are outside of the scatter in the data. This implies that material anisotropy should be considered in designing highly loaded components.

Component peculiarities typical of the injection molding process must also be considered when designing highly loaded components of LCP's. The tensile property tests showed a strong tendency for specimens to break in the "cold shot" region near the end of the injection flow length at the mold boundary. Material weakness due to localized flow cooling or flow covergence lines must be very carefully considered when designing highly loaded parts. Rocket motor and engine components are both highly loaded and subjected to extreme environments.

Applications and Results:

Liquid Crystal Polymers have been considered for application to several rocket motor and engine components. Their high strength, good thermal stability, coatability, and solvent resistance makes LCP's attractive for both solid and liquid system nozzles, or nozzle substructures, solid rocket cases and igniter cases, liquid propellant inducers, pump housings, and tankage. Several small demonstration articles have been molded and tested to determine the feasibility of using LCP's for rocket components. The test articles are: 2X4 solid motor cases, hybrid demonstrator nozzle plugs, and liquid propellant compatibility test articles.

2X4 Solid Motor Cases

2X4's are small, 2 inch diameter, 4 inch long solid rocket motors used to test propellant ballistic properties. The 2X4 motor cases are currently made of steel and are reusable. However, they provided an interesting, inexpensive, and relatively low risk vehicle for testing the application of LCP's to solid motor cases. Cases were injection molded of Vectra A625 (25% carbon flake filled), Vectra C130 (30% choppped glass fiber filled), and Ryton (30% glass filled PPS) with both 1/8 and 1/4 inch wall thicknesses. Of the 11 motors fired with 1/8 inch wall thickness, 4 failed due to over-pressurization. The maximum internal pressure achieved was approximately 1300 psi. The cases were designed to achieve approximately 2300 psi using the manufacturers' strength and modulus data. Using material properties generated from in-house testing, the cases should have been able to maintain pressures of 1100 to 1400 psi. This difference in design pressures illustrates an important point. As with many other composite materials, the translation of material properties from manufacturer's data to "as produced" parts is not good. In this case, the "as molded" part strength is only half of the manufacturer's calculated value.

Hybrid Demonstrator Nozzle Plugs[2]

The Hybrid Demonstrator is a simple hybrid engine with a polyurethane core and gaseous oxygen as the combusting agent. Small plugs were molded to fit the nozzle assembly of the demonstrator to provide long duration heat exposure and thermal shock information on the LCP's. All the materials tested were neat resins: Xydar SRT 300, and SRT 500, Vectra A950, and HX400. Tests ranged in duration from 1 to 22 sec and from 50 to 90 psi internal pressure. Significant charring and erosion were noted on all plugs, even after 1 sec of flame exposure. However, all the plugs survived the thermal shock of engine ignition. Loss of structural integrity occured between 15 and 22 sec for all the materials tested.

Liquid Propellant Compatibility Test Articles[3]

Compatibility tests were conducted on 1/2 inch diameter disks of 8 different LCP's and PPS soaked from 24 hrs to one week in Monomethyl Hydrazine (MMH) and Nitrogen Tetroxide (NTO). The materials tested were: Vectra A950, C950, A625, A130, B230,

HX4000, Xydar SRT 300, Xydar RC210, and Ryton. The HX400 released potentially dangerous by products when soaked in MMH. The vectra A625 lost 3.2% of its weight after 24 hrs in MMH. Vectra A950 gained 0.84% weight after 24 hrs in MMH. The HX4000 lost over 50% of its weight after 24 hrs in MMH. Weight changes where as small as 0.02% (Xydar RC210) after 24 hrs in NTO. The weight of HX4000 changed the most in NTO, also, losing over 7%. After one week in MMH, Vectra C950 lost 11% weight, Vectra A625 lost 22% weight, and HX4000 almost completely disintegrated. Both the Xydar SRT 300 and Xydar RC 210 maintained 99.9% of their original weight after a week immersed in NTO.

Conclusions

Several "quick and dirty" tests have been conducted on Liquid Crystal Polymers to determine their suitability for use in rocket motor and engine components. Although not all of the tests have been completely successful, they have provided valuable insights into LCP processing, part design, and material performance. Many LCP's, due to rapid melt transitions and high temperatures, have very tight processing windows. Component weaknesses from flow cooling or flow covergence require careful mold design, mold temperature control, and careful part design. The translation of material properties from manufacturer's data to "as molded" part performance is not efficient. This poor translation requires that thorough screening and mechanical properties tests be conducted on candidate materials and processing techniques to determine suitable design parameters.

In spite of the difficulty of applying LCP's, these polymers present several interesting properties that require further research. A pronounced "skin and core" effect, where the material near a part surface is more molecularly oriented, therefore stronger, than material closer to the centerline of the part, implies that the structural efficiency of LCP parts decreases with increasing part thickness. This effect may develop into strong, damage tolerant thin structures. Some LCP's may undergo a type of "physio-chemical annealing" that eliminates the melt temperature transition and increases the polymer degradation temperature. This "annealing" phenomenon, if properly developed, may lead to light weight polymer parts for high temperature applications.

Future research being conducted by Phillips Lab will include examination of the annealing behavior of Liquid Crystal Polymers, design property characterization of these materials, processing effects research, and further component development.

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Design of a Blow Molded LCP Pressure Vessel and a Fiber Reinforced Pressure Vessel.

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Abstract

Three pressure vessel with a length of 35 inches, case diameter of 10 inches, and an internal pressure of 3500 psi were designed. Two separate types were analyzed, an unreinforced Liquid Crystal Polymer (LCP) and a S-glass/LCP reinforced pressure vessel. Two cases were assumed for the unreinforced LCP the best weight 17.5 lbf; a realistic, conservative design would weight 33.5 lbf. An unreinforced spherical pressure vessel weighting 21.4 lbf was also designed. The reinforced pressure vessel weight 3.00 lbs. Further study of LCP flow patterns and fiber/LCP interaction is recommended.

Approach

There are two sections to this report. The first deals with a LCP pressure vessel. The second deals with a S-glass/LCP reinforced pressure vessel with a LCP bladder. The pressure vessel with design requirements are shown in figure 1. The material properties of LCP and S-glass are shown on tables 1 and 2.

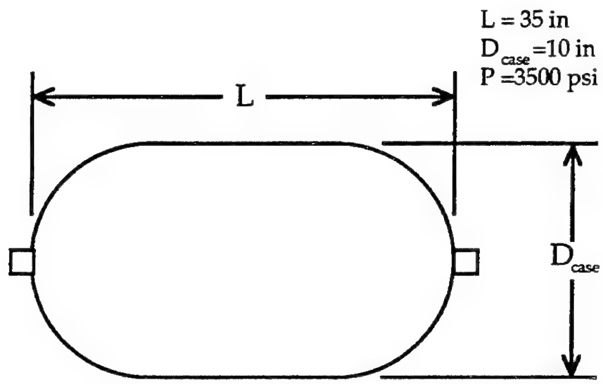

Figure 1. The Pressure Vessel.

Table 1.
LCP Properties

X	40 ksi
Y	20 ksi
ρ	1.4 g/cc

Table 2.
S-glass Properties

X	665 ksi
Fiber Vol.	67 %
ρ	2.5 g/cc
Bandwidth	.25 in

LCP Pressure Vessel

LCP behaves anisotropically, but the orientation is unknown, therefor thin walled pressure vessel theory is used for analysis. The polymer chains are assumed to align either parallel or perpendicular to the bottle axis. Two designs are examined that cover the both possibilities. This is the best that can be done until further investigation shows specific LCP chain orientation.

The interaction of forces would most likely give an in-between orientation. The exact orientation will remain unknown until the study of LCP advances. Additional problems include the blow molding process. When the paranon, unformed plastic, is injected into the mold cavity damage to the polymer chain by a screw might occur. The screw develops pressure to inject the paranon into the mold cavity. If long polymer chains are to be maintained the screw action would probably damage them.

Parallel Alignment

Shearing forces would probably make the LCP chain orient or align itself longitudinally during the injection step. This would give a polymer chain alignment pole to pole, shown in figure 2.

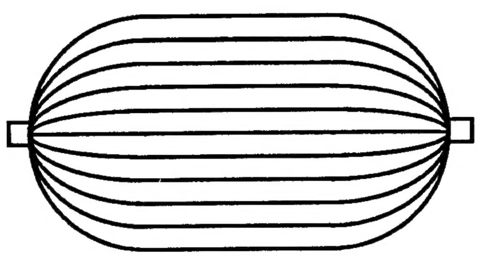

Figure 2. Longitudinal Polymer Chain Alignment.

A LCP parallel alignment would require a case (hoop) thickness of .875 inches and dome thickness of .21875 inches, shown on table 3. The additional hoop thickness is required to balance the hoop forces. Since the blow molding process cannot control thickness, the wall thickness will be determined by the weakest section, in this case the hoop section.

Table 3.
Longitudinally Aligned

t_{case}	t_{dome}	Safety Factor	Weight
.875 in	.21875 in	1.5	33.5 lbf

Perpendicular Alignment

The other possible alignment is the polymer chains aligned cylindrically, shown in figure 3.

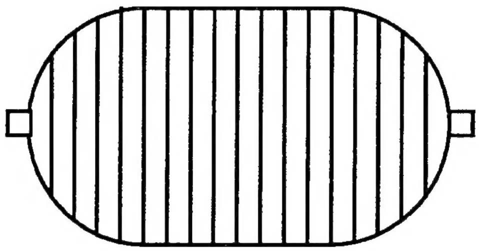

Figure 3. Hoop Alignment.

The dome and case thickness are equal with a perpendicular alignment, shown on table 4. This would be the optimal alignment. However, the shearing forces might make this the most difficult to achieve.

Table 4.
Hoop Alignment

t_{case}	t_{dome}	Safety Factor	Weight
.4375 in	.4375 in	1.5	17.5 lbf

Spherical Design

The weakest area is the cylindrical section. A spherical pressure vessel, which would avoid this problem, assuming parallel alignment and equal internal volume would have the characteristics shown in table 5.

Table 5.
Spherical Pressure Vessel

Diameter	t	Safety Factor	Weight
20.4 in	.665 in	1.5	21.4 lbf

Fiber Reinforced Pressure Vessel

The fiber reinforced pressure vessel was designed with the same requirements as the LCP only design. Netting Analysis was used to analyze the pressure vessel which assumes only the fibers are being loaded. It does not include fiber/matrix or composite/bladder interaction. A more complete analysis is being done using laminate plate theory. A boss diameter of 1 inch is assumed. The weight, shown on table 6, is substantially less then the unreinforced LCP.

Table 5.
Fiber Reinforced Pressure Vessel

t_{case}	t_{dome}	Safety Factor	Weight
.070 in	.071 in	1.5	3.00 lbf

Recommendations

The fiber reinforced LCP pressure vessel is the best design if weight is the only consideration. If production time is a consideration and the weight penalties are acceptable, then the unreinforced LCP design would be better.

Before any designs are considered, careful study of LCP flow patterns must be investigated. The LCP chain orientation is extremely critical for any unreinforced pressure vessel. Proper fiber/matrix interaction to ensure good bondage and proper fiber volume must also be studied.

LCP Material Properties						Fiber Material Properties				
X =	40000	psi				X =	665000	psi		
Y =	20000	psi				Band Width =	0.065	in		
E1 =	4000000	psi				Yield =	0.64193064	g/m	3.5946E-05	lbf/in
E2 =	2000000	psi				rho =	2.49	g/cc	0.08995548	lbf/in3
						Fiber Volume=	0.67			
rho =	1.4	g/cc	0.05057738	lbf/in3		Ef =	12600000	psi		250
					in					0.00011111
Pressure Vessel										
P =	3500	psi	D,boss =	1						
D,case =	10	in								
L =	35	in				Fiber Reinforcement				
Safty Factor =	1.5									
						Fiber Angle =	5.7366919	deg	Area End =	0.0003996
LCP Only Design					in	t,c =	0.05861839	in	Plys =	9.54
Longitudinal Allignment			Cylinderical Allignment		in	t,l =	0.02960638	in	Plys =	4.82
t,c =	0.875	in	t,c =	0.4375						
t,l =	0.21875	in	t,l =	0.4375	in					
						V =	27.6006442	in3		
t,max =	1.3125	in	t,max =	0.65625	in3	W =	2.12416499	lbf		
					lbf					
V =	662.170687	in3	V =	345.868709						
W =	33.4908559	lbf	W =	17.4931318						
Longitudinal, Spherical Design										
D =	20.4082755	in								
t =	0.66964654	in								
V =	424.069969	in3								
W =	21.4483464									